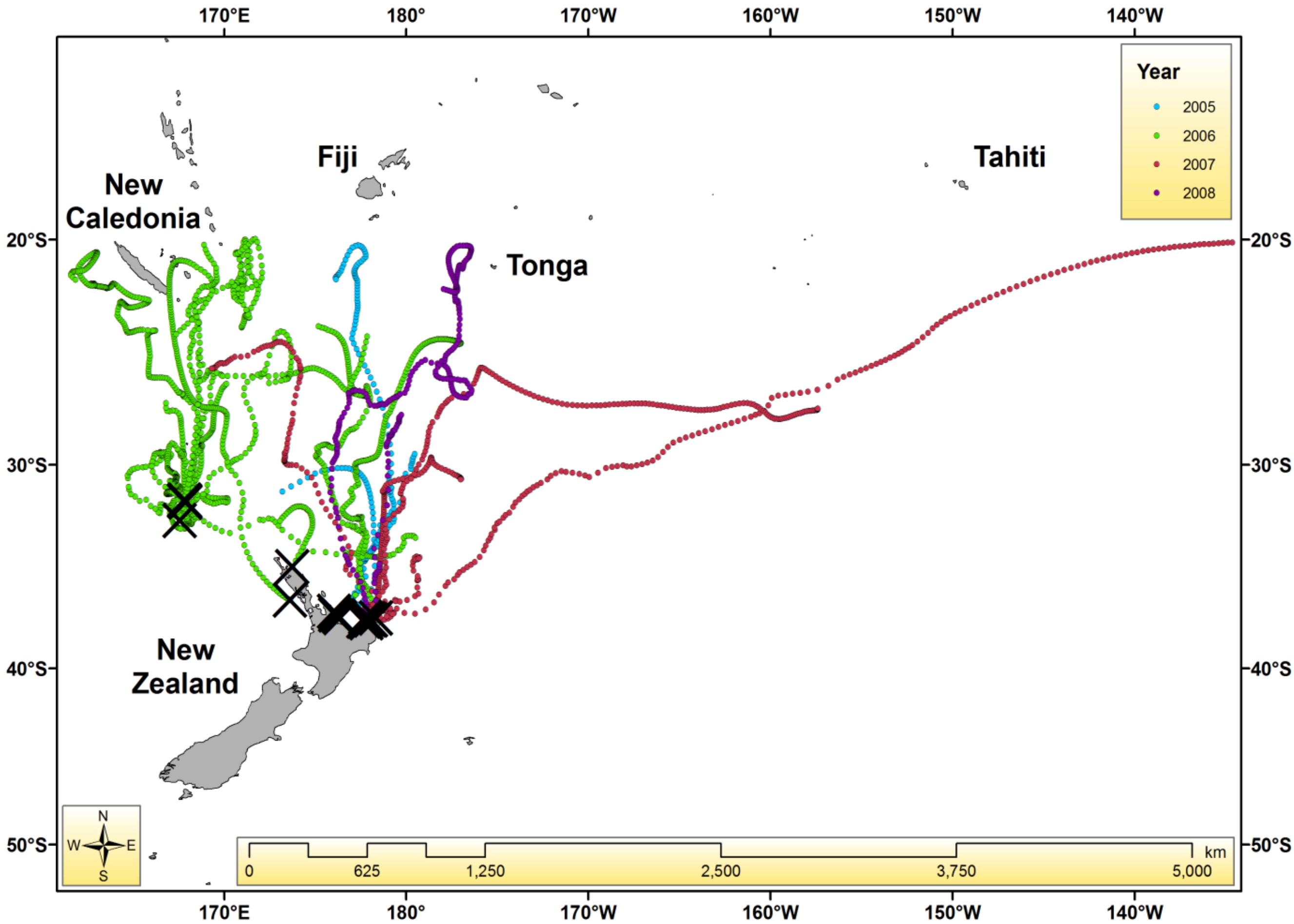
Striped marlin satellite tagging in New Zealand: Summarizing the Foundation's research program



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EXECUTIVE SUMMARY

This is the fourth report in a series updating the status of striped marlin satellite tagging research funded from the New Zealand Marine Research Foundation's initiatives. Since 2003 the Foundation has been the primary funder of this New Zealand based research program, with numerous other major contributors and through both domestic and international scientific collaborators. Previous reports to the Foundation have focused on new data being gathered during the course of the program, up to and including the 2007 season. Since then, three more striped marlin were satellite tagged during the 2008 season, with two providing data, including the most detailed track yet. The third and final deployment in 2008 was an experimental deployment culminating from attempts over three seasons to free tag striped marlin without capture on fishing gear.

Since the 2007 report, research efforts have shifted from gathering data to analyzing and interpreting data. As has been discussed in detail previously, two kinds of satellite tags have been used to study the movements and behaviours of striped marlin. The qualities of these two kinds of data are distinctly different, and surprisingly challenging to combine. The numerous challenges of analyzing and interpreting marine telemetry data are topics of ongoing international efforts, and a recently developed model helped solve issues with combining all striped marlin data into a coherent dataset.

With complete striped marlin telemetry datasets available, effort was put towards developing a model of behaviour, aimed at inferring when and where striped marlin feed and migrate. The result is a new view of striped marlin, which when combined with the depth data gathered from satellite tags provides a view of behaviour in three dimensions through time. A surprising result has been observations of multiple fish reversing directions in the tropics afterreaching 20-21°S latitude. This might help understand the distribution of the species in the southwest Pacific Ocean. Results from behavioural modeling are also helping understand how they respond to the capture and tagging process itself.

A natural progression from these efforts is interest in the role oceanography and the environment play in shaping their behaviour and distribution. Distribution of striped marlin in the Pacific Ocean is complex, with our corner including the southwest Pacific and Tasman Sea demonstrating its own complexity. Distributions of observed locations were divided into two eco-regions, the Tasman Sea and southwest Pacific sub-tropical gyre. The oceanographic complexity, combined with this being among the most poorly understood oceanic regions in the world means we are dealing with a double edged sword. These telemetry data are uniquely valuable at helping understand the biological relevance of regional oceanographic characteristics, but the poor baseline knowledge means analysis and interpretation are clouded with uncertainty.

The fascinating new information collected here has widespread value, ranging from basic biological understanding to critical insights to help inform species management in the southwest Pacific Ocean. At least seven different exclusive economic zones were crossed by striped marlin from this research program, as far afield as French Polynesia. The highly migratory nature of the species means that population management can not occur in isolation, with individual nations setting national priorities without regard to wider regional implications. Their recreational value in New Zealand is indisputable, and the recreational gamefishing community has made critical contributions towards ensuring its value is recognized by supporting this research.

Previous reports have utilized a format similar to scientific journals by including an Introduction, Materials and Methods, Results, and Conclusions. This report will focus on outcomes and summarization, while background and specific information about methods can be found in previous reports.

Behaviour and Oceanography

In order to estimate behaviours from telemetry data which are highly variable in location frequency and accuracy, a statistical model called a Kalman filter proved to be invaluable in several ways. In short, the Kalman filter is a statistical framework which provides improved confidence in locations from our tagging methods. It was also a useful framework for taking all of the data we have of variable spatial resolution to produce a regular time-series of locations. Statistically, it is difficult to deal with irregularity in time and space at the same time, so marlin tracks were estimated on regular time-scales (every 12 hours) so only spatial variability remained to be analyzed. Tracking summarized by tagging season illustrates some of the common and unique observations across years (see Figure 1).

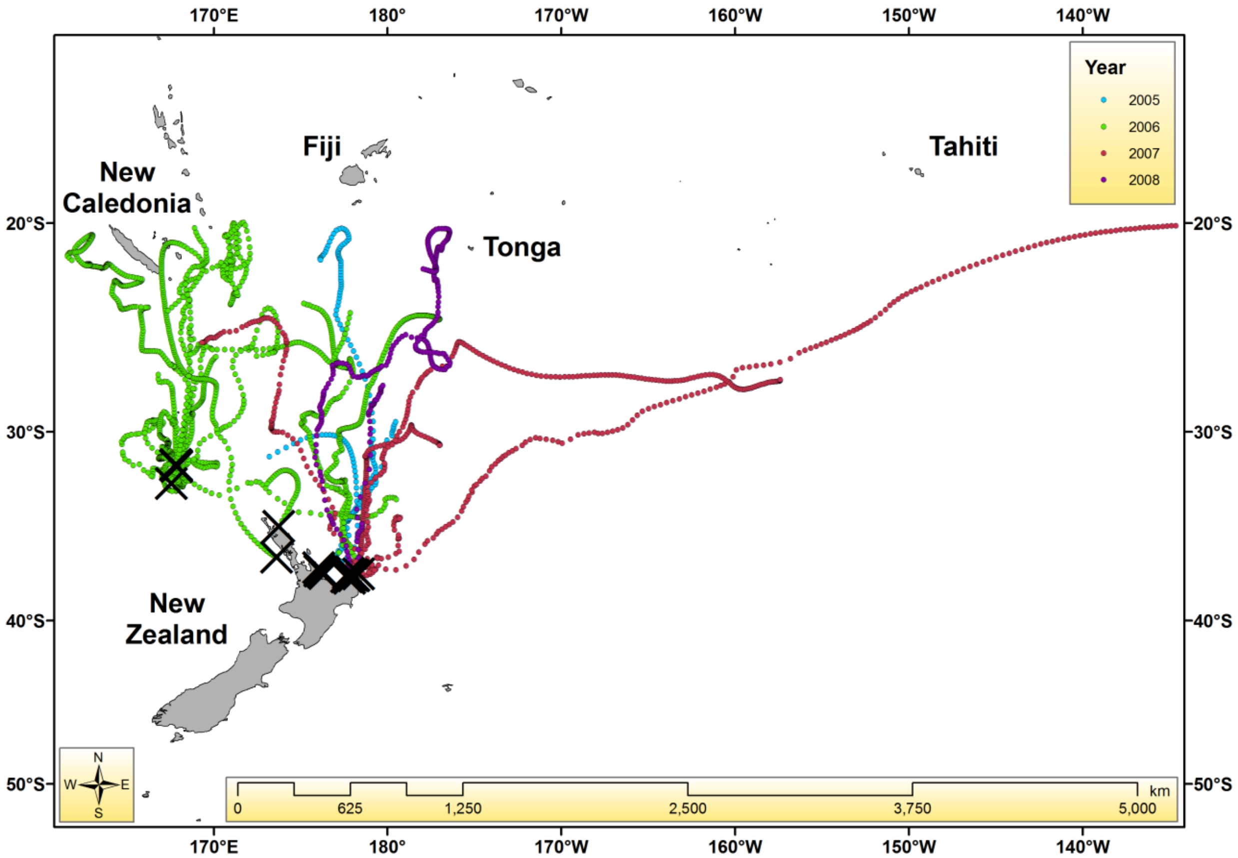

Figure 1. Twenty seven striped marlin trajectories from tagging during 2005-2008. Using observations from the satellite tags, statistical models were used to estimate each striped marlin track every 12 hours. 'X' marks tagging locations for each fish.

When looking at these tracks individually, there are all kinds of interesting patterns like loops, long straight segments, directional reversals, etc. Ecological theory suggests that different behaviours can be identified by making a few assumptions about the structure of these segments. Two basic behavioural ‘categories’ can be extracted, straight segments, and non-straight segments. Migration, pursuing prey and fleeing predators are likely to be represented by straighter segments. Foraging, breeding and resting are consistent with high turning frequencies and can simply be called ‘Area Restricted Behaviours’ (ARB). Since marlin breath by swimming continuously and breeding occurs at different times than these data were collected, we exclude the possibility of ARB representing those behaviours and assume it primarily represents foraging. However, these are only our best estimates, and we can’t be certain what is really happening during ARB and transitory behaviours. Mathematically estimating how to characterize behaviour is challenging because determining where and when behavioural switches occur in a trajectory segment when seemingly random twists and turns and changes in speed arise is difficult. Scientists who are interested in the genetic make-up of organisms from looking at DNA devised a statistical solution to a similar problem, and ecologists have recently adapted the genetic solution to animal trajectory analysis. If an animal trajectory is thought of like a DNA sequence, then a unique behaviour within the trajectory can be considered to be similar to a gene within the DNA strand. Thus a technique designed to identify genes has been applied for estimating striped marlin behaviour. In addition to transitory behaviour and ARB, changes in speed were also detected, giving a four mode model of slow-transiting, fast-transiting, slow-ARB, and fast-ARB. Figure 2 shows striped marlin trajectories divided into segments using these methods.

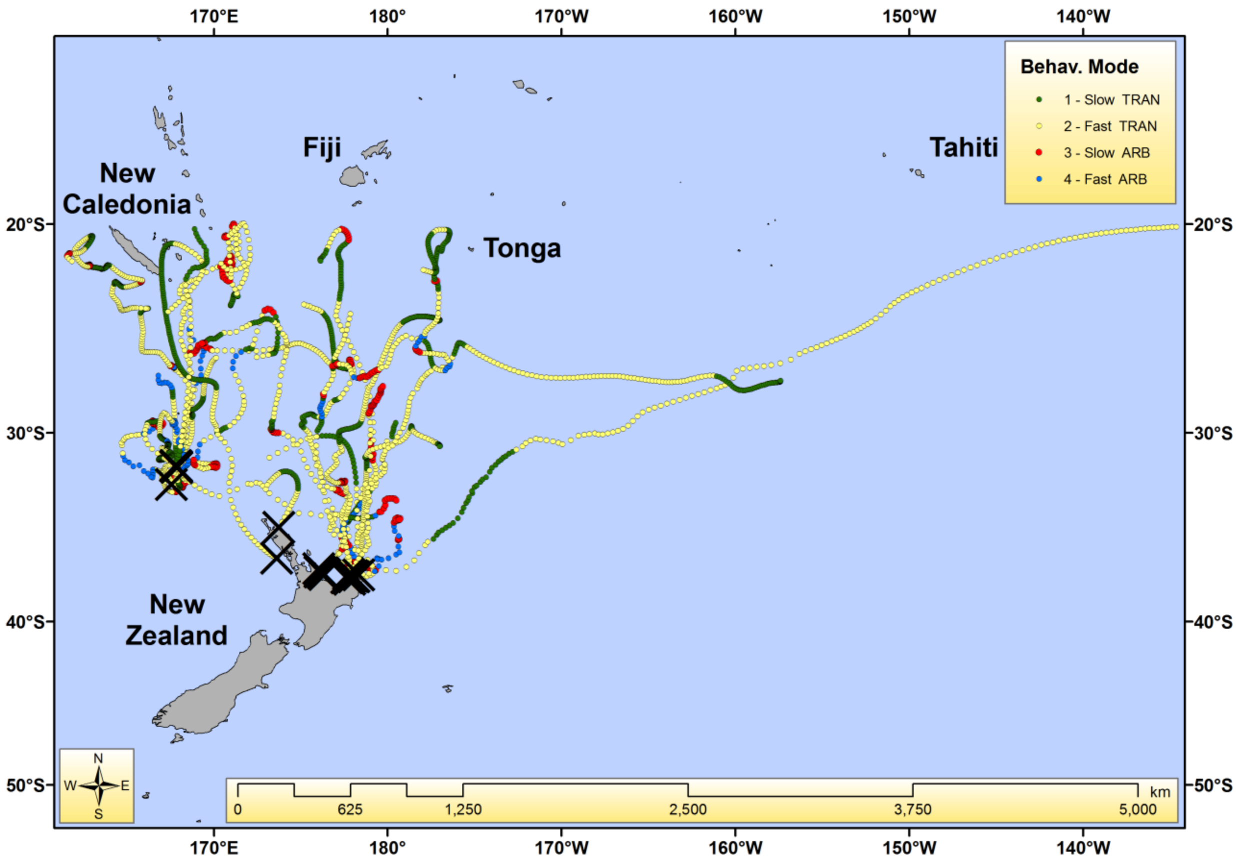

Figure 2. Striped marlin tracks divided in straight segments (called ‘Transiting’) and turning segments (called ‘ARB’), and divided by periods when they are traveling faster or slower than the median speed for each animal.

As you probably recall from previous reports, the pop-up satellite archival tags (PSAT)s also collected information about the diving behaviours of striped marlin. Changes in depths for individual marlin are useful for many reasons. These diving patterns were compared to behaviours estimated by the model above, to see if there is a relationship between behaviour and depth. In fact, transitory behaviours were on average deeper than ARB. If the assumption that ARB usually represents foraging holds, we can say that striped marlin tend to feed at shallower depths than they travel at. One way this could be interpreted is transitory behaviour represents a search for more food, and thus they dive more through the water column in search for food. When they encounter plentiful food, they tend to stop searching (when you find the food, you stop looking for it!). This is only a general trend, but there are exceptions to every rule. The frequent match between depth distributions and estimated behaviours provides a measure of confidence that the model is making meaningful estimates. However, the kinds of prey available through time will change, and foraging on pilchards (near the surface in daylight) vs squid (deeper during the night) will look different to a behavioural model like this, and detecting these differences is probably not always possible. Satellite tagging in the eastern and central tropical Pacific have been seldom observed striped marlin deeper than 75-100m. The data collected here tell a different story, demonstrating striped marlin spend more time at depth including a maximum depth of 428m (13.2°C). See Figure 3 which shows the diving profile of one marlin through time.

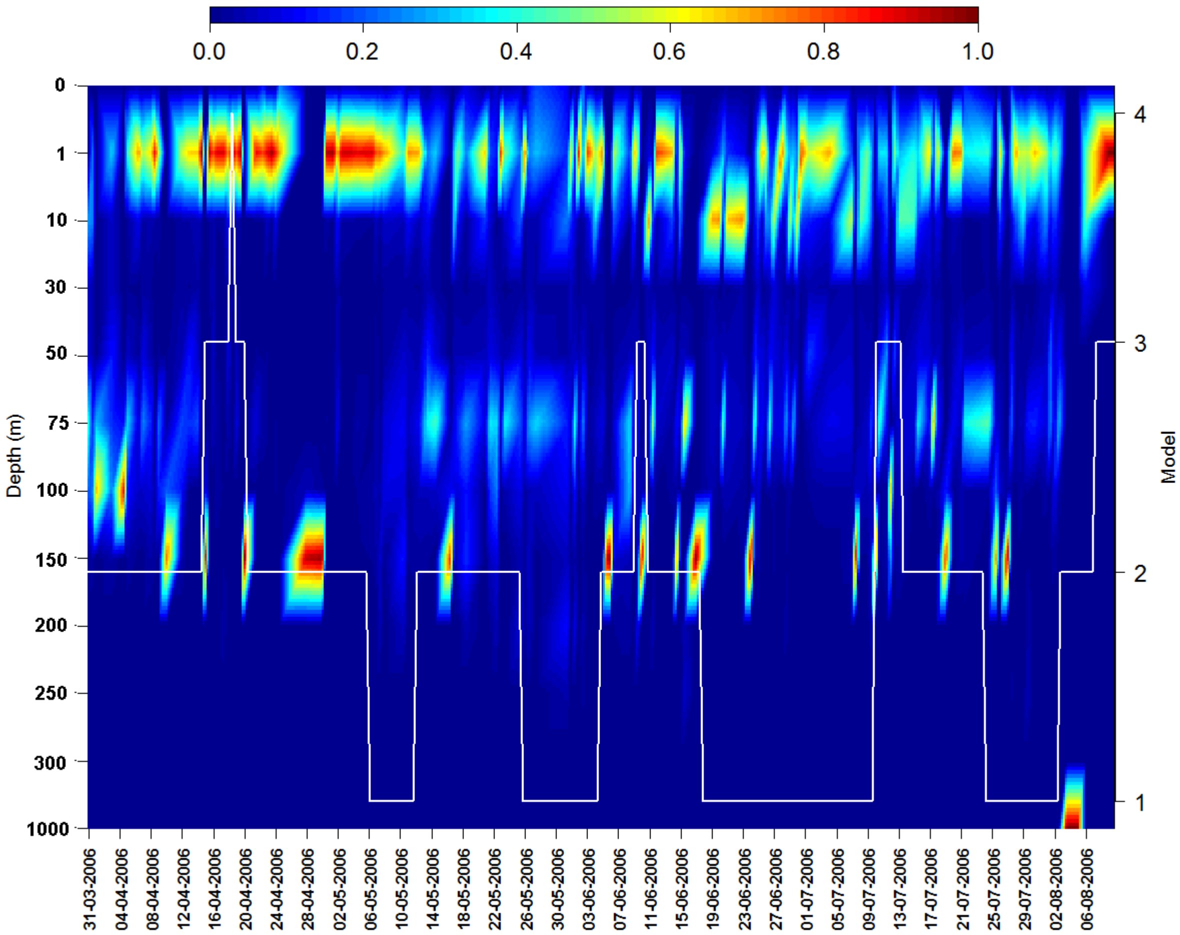

Figure 3. Changes of depth and behaviour through time for one striped marlin. The x-axis is time (bottom), y-axis(left) is the depth of the animal below the surface, colour represents the proportion of time spent at depth (yellow represents 60%), and the white trend line represents the estimate of behaviour (right) by the model (Mode 1 = Slow-transit; Mode 2 = Fast-transit; Mode 3 = Slow-ARB; Mode 4 = Fast-ARB).

A total of three PSAT tags have washed up on beaches in Australia and have been returned to the program. The recovery of these tags has provided the highest quality data possible, with water temperature, diving depth and sunlight intensity recorded every 30-60 seconds. This highly detailed data were included in the behavioural modeling, and the outputs for one fish, STM06-1 can be seen in Figure 4. Note the erratic diving patterns displayed during the first ~10 days after tagging (first and second panels) followed by more 'normal' patterns later in the track (third panel). The third panel also shows the general correspondence of depth distributions and behaviours estimated by the model. Some overseas research has explored how pelagic fishes like marlin might conserve energy by using different swimming modes to maximize efficiency. The idea is that the animal drifts down through the water column passively, and then returns to the warmer surface waters actively swimming. Although this hasn't been explored in detail with these marlin data, the rates of ascent (return to the surface) and descent (dive deeper) appear similar most of the time in Figure 4.

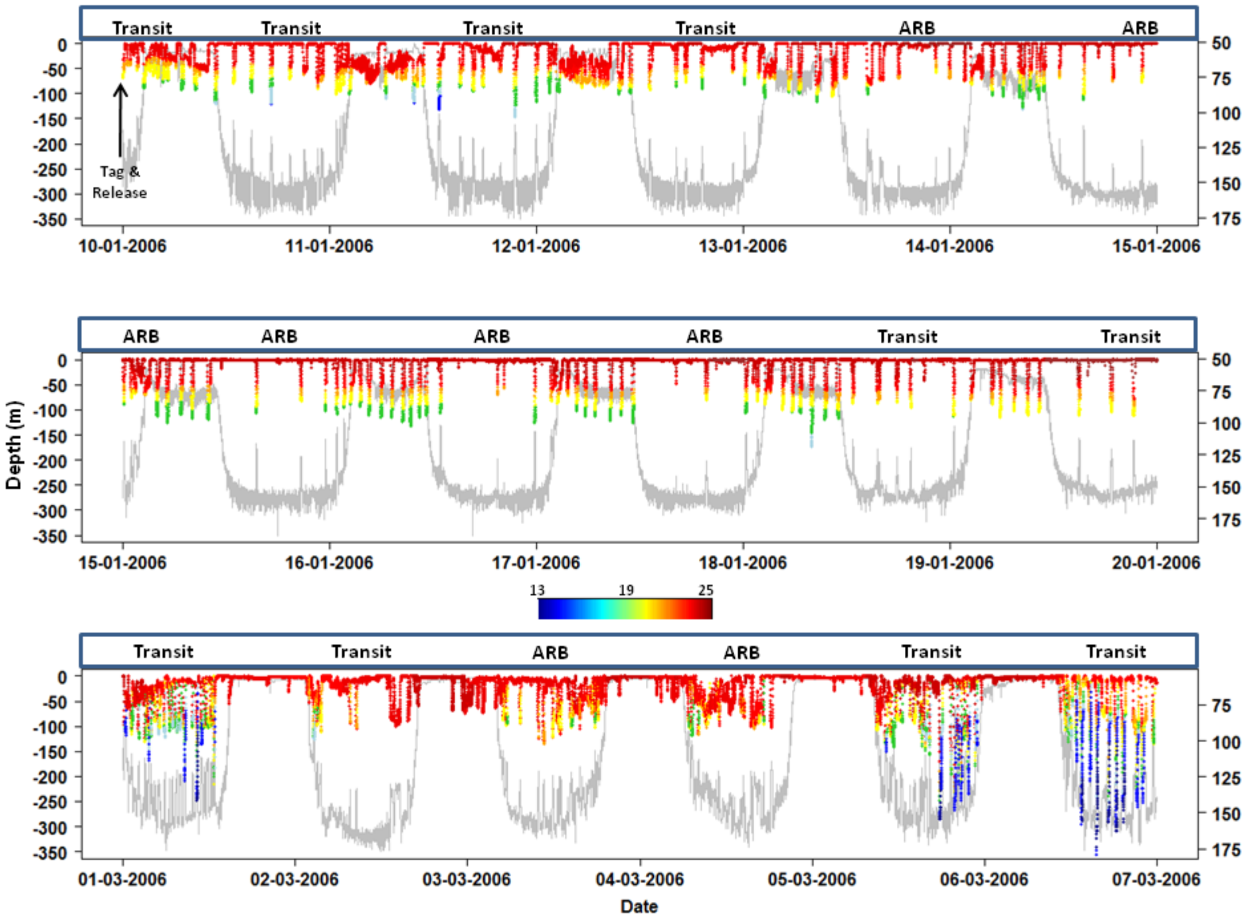

Figure 4. Archival time series for STM06-1. The colour of the lines represents water temperature (see corresponding colour scale in the middle), with depth on the y-axis (on the left), time on the x-axis (on the bottom), and the light grey line represents sunlight intensity (scale on the far right without measurement units). Periods of day are apparent from the 'bowl' shaped light grey lines on the plots, and night is the period between each grey 'bowl'. The estimated behavioural mode is labeled above each day.

One of the most interesting satellite tracks was gathered in 2008. STM08-1 was an 80kg striped marlin tagged on 6 March 2008 at Waihau Bay from Clyde Fraser's boat. Over the ensuing ~4 months it travelled to the tropics, transmitting locations when it surfaced, until the battery in its tail mounted SPOT tag finally went flat 115 days later on 29 June 2008. This was the longest and most detailed tail tag track gathered in the program, after several years of refining our methods. As it made its way north, it changed course numerous times, making loops followed by straight periods, and eventually reached 20°S latitude west of Tonga before reversing directions and heading south again. As most marlin did, it also moved away from its tagging location immediately upon release, not returning to the initial capture area that same season. Figure 5 shows the trajectory and changes in behaviour.

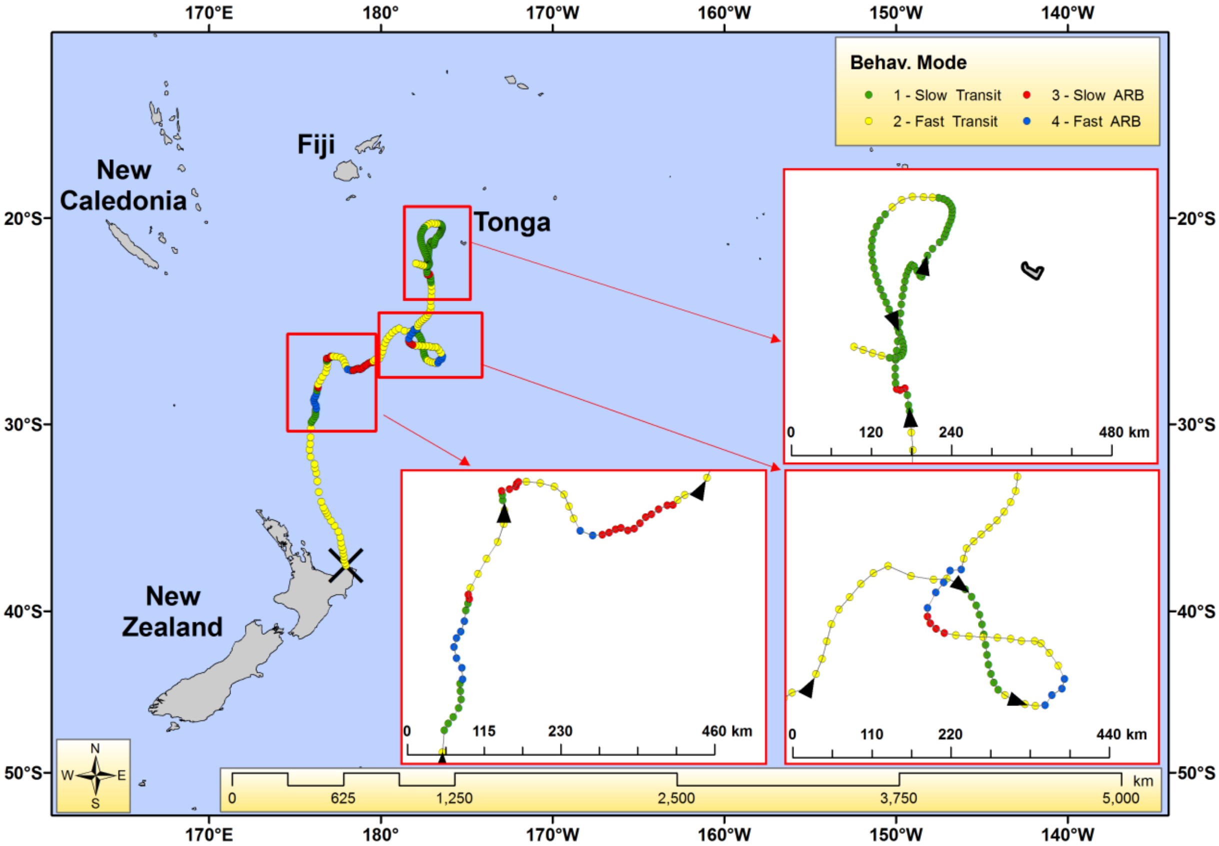

Figure 5. Behavioural model estimates for STM08-1. Note the numerous behavioural switches in the track and its directional reversal in the tropics. This illustrates the behavioural complexity of striped marlin movement which could not be reliably detected without the development of statistical models such as this.

Striped marlin seldom remained within the same general area of initial capture after being tagged and released. However, some did return to the initial capture vicinity weeks later, but the probability of their returning was related to the time of year of the initial capture. Of the fourteen tagged before 1 March of any year (2005-2008), five either returned to the general tagging area or began circling back in that direction (see Figure 6). None of the 11 tagged after 1 March did this. Furthermore, none of satellite tracked marlin were in or around New Zealand coastal waters after March, and by April they were generally north of 30°S latitude, or headed that direction (see Figure 9). Given some of the best striped marlin fishing around New Zealand traditionally occurs during March and April and sometimes May, it is curious that none of the tagged marlin were found here. This suggests the capture and/or tagging process might contribute to their departure from New Zealand and Tasman capture locations sooner than they would if they hadn't been captured. An attempt to understand this was made by attaching a PSAT tag to a marlin from a free-diver's speargun at the Wanganella Banks. The purpose was to compare the behavior of an uncaptured marlin with the behaviours observed in fish captured on recreational fishing gear. This was the final deployment of the program, after three seasons trying to make this happen. Unfortunately, the tag never reported data back.

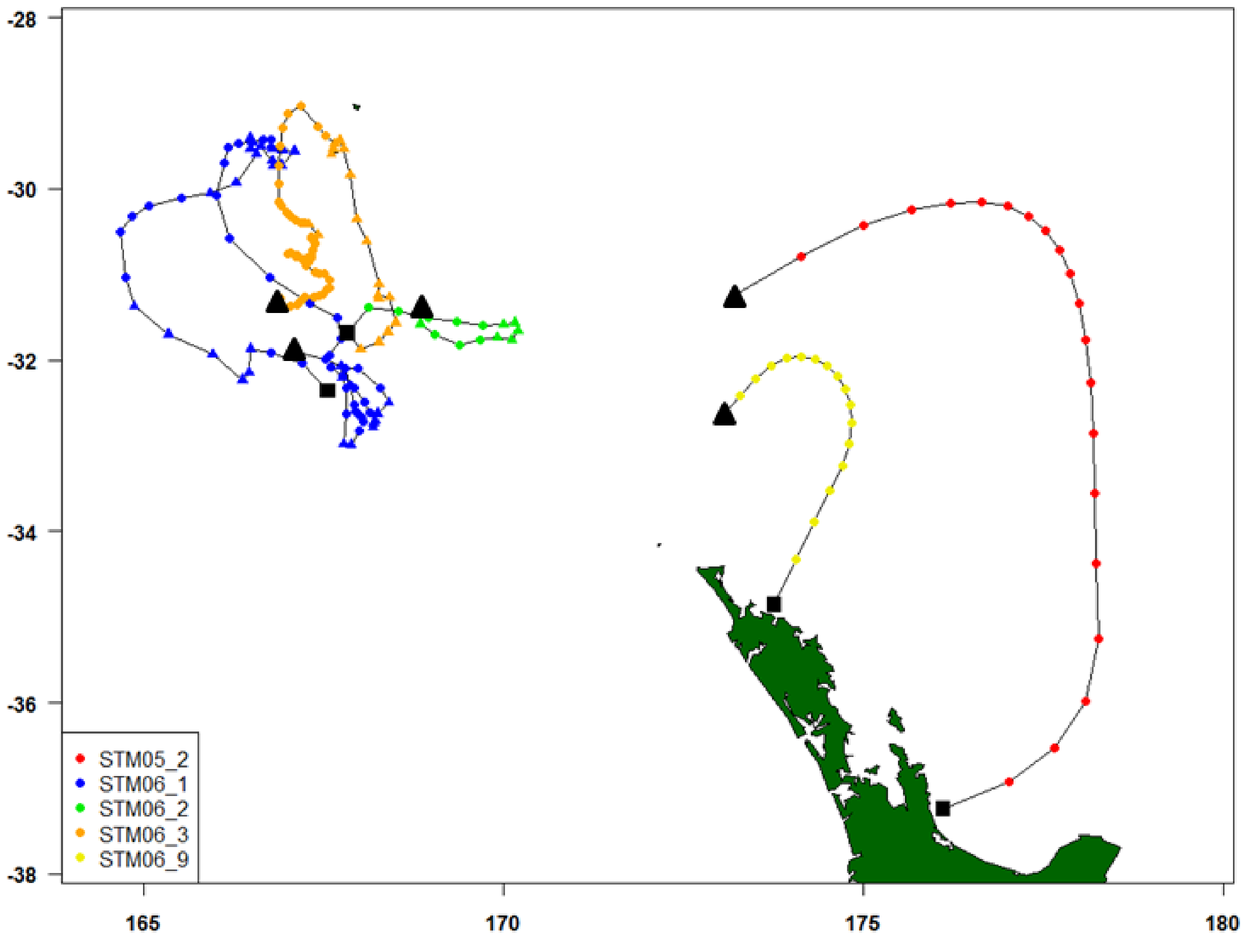

Figure 6. Five striped marlin tagged before 1 March either returning to their initial capture locations, or heading back in that direction.

Six different striped marlin reversed directions or halted northerly progress in the tropics between 20-21°S during each tagging season (2005-2008), within all months from April-August. One marlin tagged in early April 2006 at the Wanganella Banks moved up to the Fiji Plateau, making at least three directional reversals as it spent May and June circling around south of Vanuatu. Another tagged at the Wanganellas in April 2006 moved north and then east of New Caledonia, making the same directional reversal at 20°S. In each case, the marlin switched into fast-transiting mode during the directional reversal, which might suggest an avoidance response (see Figure 7). Analysis of the oceanography associated with this behaviour indicated changes in mixed layer depth, local bathymetric gradients, and sea surface height contributed to this behaviour (see Figure 8). Water temperatures were not the only factor, as they ranged from 24-29°C at the time of reversals.

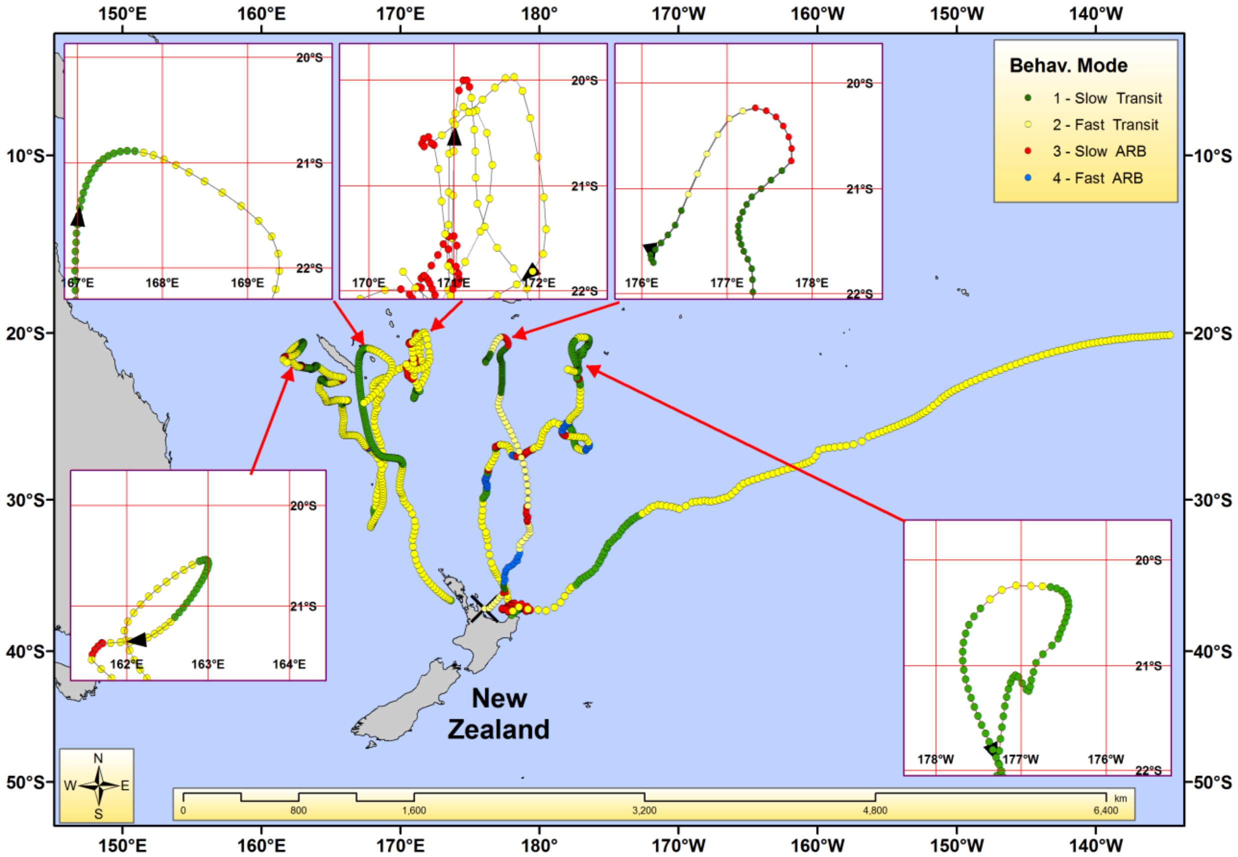

Figure 7. Directional reversals of five striped marlin which reversed directions in the tropics (see insets), and one which halted northerly progress at 20°S latitude (track moving into the central Pacific Ocean, not inset).

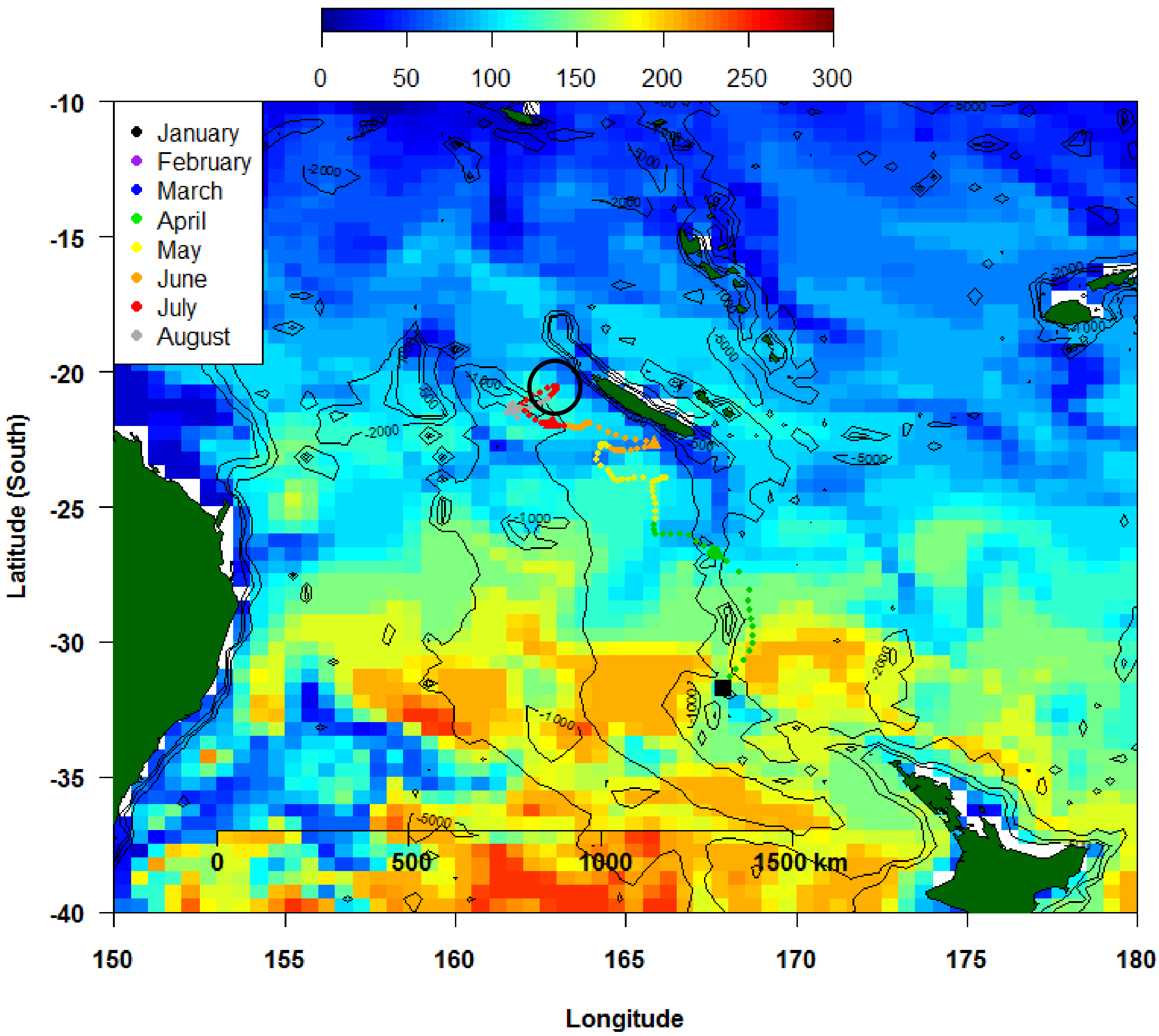

Figure 8. Track for STM06-10 plotted over depth of the ocean's mixed layer and bathymetric depth. The marlin's track is represented by the colored symbols, with circles (●) representing transiting behaviour, triangles as foraging behaviour (▲), and the initial tagging location a square (■). The symbols are coloured by month of the year, and the legend at top-left indicates the colours for different months. The background colors for the map represent the depth of the mixed layer on 25 July 2006, when the fish reversed directions at 20°S latitude west of New Caledonia (circled in black at the northern most location of the fish before reversal). Colours used to indicate mixed layer depth are in the bar at the top of the map, so blues equal shallow mixed layers (0-50 meters), green-yellow are mixed layer depths 150-200 meters, and reds are deep mixed layers (deeper than 200m). Depth contours at 500, 1000, 2000, 5000 meter outlined and labeled in black on the map.

Assessment of the oceanographic drivers of striped marlin behaviour and distribution is complex. Are there defining characteristics of striped marlin behaviour? Can we predict their distributions with oceanographic data? Tracking the movements of striped marlin and many other marine organisms is exciting, but it only tells us what they are doing at the ocean's surface. Oceans are very complex, with the vast majority of oceanographic and biological activity occurring below the surface. Oceanographic complexity is also unique at different spatial and time scales. The trajectories of striped marlin gathered by this program have been sub-divided into 'eco-regions' and seasonal quarters. The two eco-regions used were the Tasman Sea (TAS) and the southwest Pacific sub-tropical gyre (SPSG), which were divided by the 173° longitude line running from north Cape to the central Fiji Plateau (see dotted black line in Figure 9). Note the track to the west of New Caledonia during June, July and August. After being tagged at the Wanganella Banks in early April, it moved into the Coral Sea, towards the areas of known striped marlin spawning aggregations which are thought to occur during October and November.

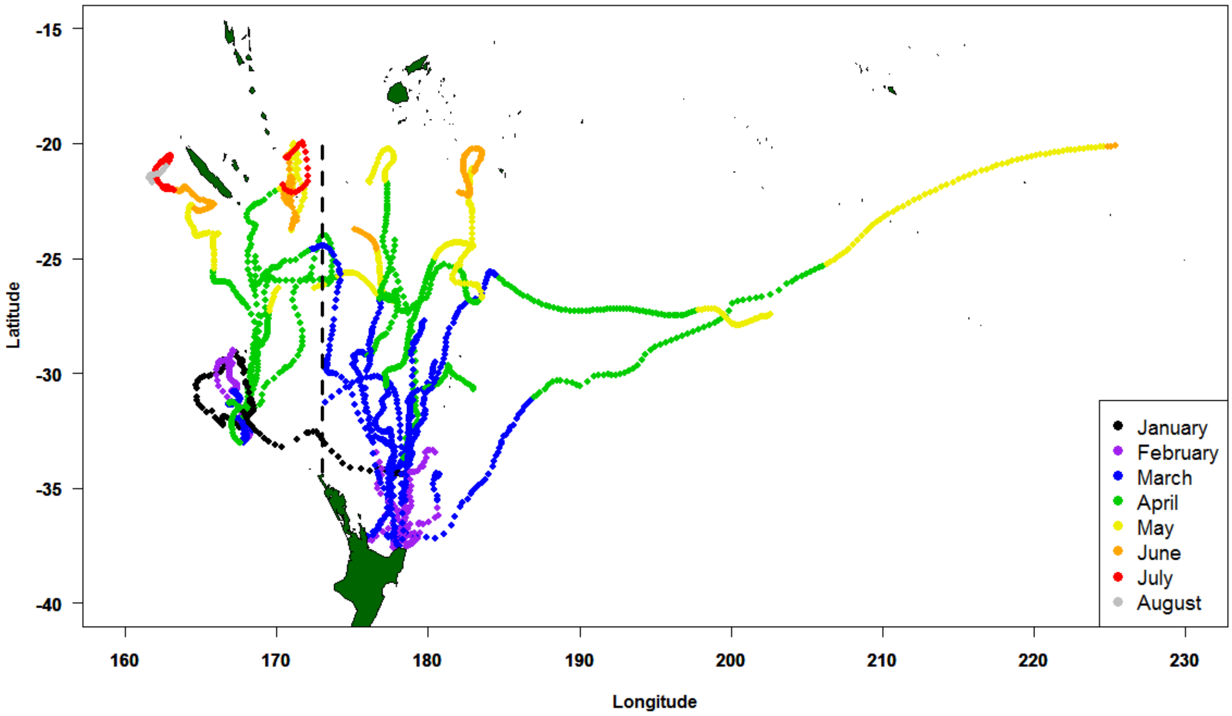

Figure 9. Striped marlin tracks used in oceanographic analysis. Locations are coloured by month of the year (see figure legend). Not all of the tracks run through the behavioural model were suitable for oceanographic analysis because of track shortness, or not enough data for the behavioural model to make useful estimates for further analysis. This figure includes only the best striped marlin tracks.

As mentioned above, the tracks were also assessed by southern hemisphere seasonal quarters. The first quarter was summer, second quarter autumn, and third quarter winter. Unfortunately, no data were available for the spring quarter. In spite of our best attempts, we were unable to collect longer term data extending into the important spring period during expected spawning. Long term (more than 4-5 months) marlin tagging data is notoriously difficult to collect. In spite of significant efforts to improve PSAT retention, premature transmissions and transmission failures remained obstacles. This difficulty has been encountered worldwide in various tagging programs on striped, blue and black marlin. The seasonal distributions of striped marlin used for oceanographic analysis can be seen in Figure 10.

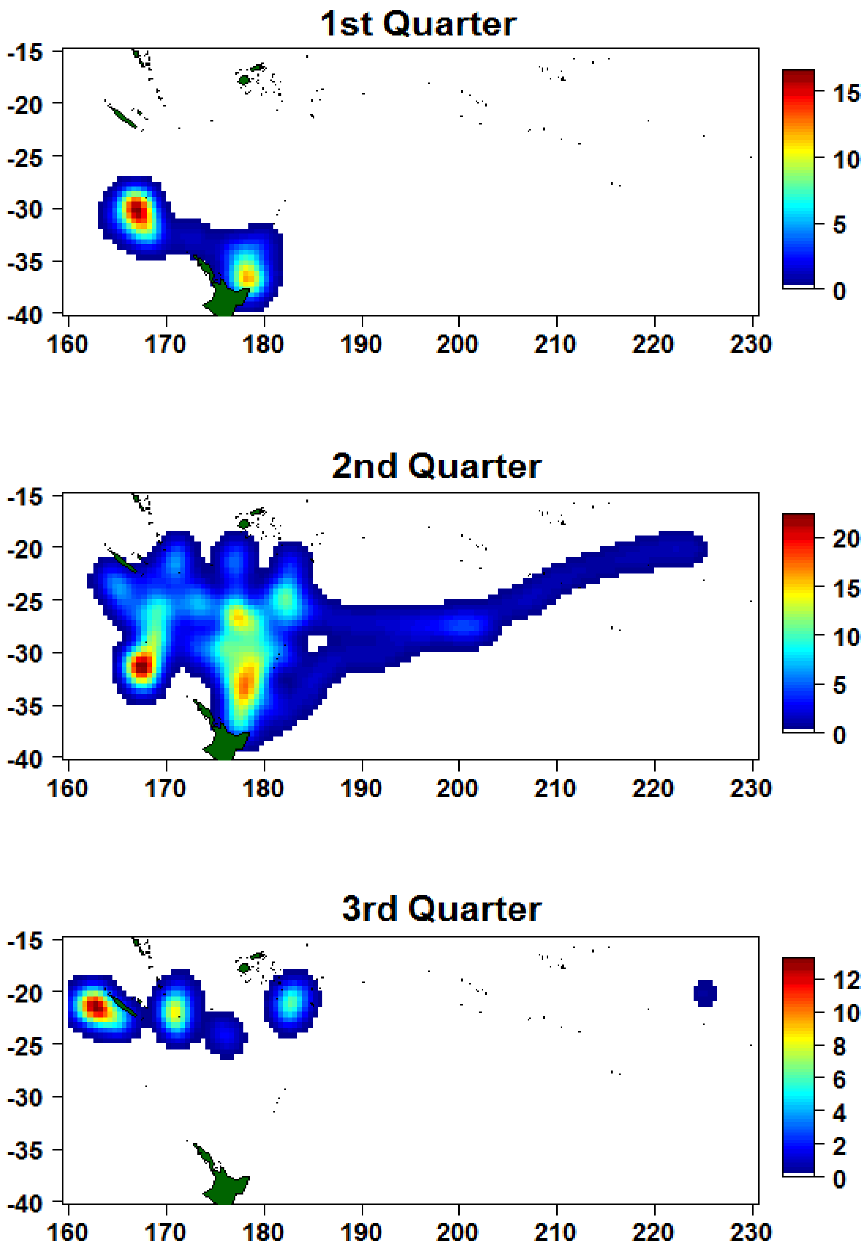

Figure 10. Quarterly distributions of striped marlin. Colours represent the ‘density’ or locations, using reds for highest ‘density’ and blues for lowest ‘density’. The colour ramp on the right of each quarterly plot indicates how many striped marlin were present per 1 x 1 degree cell.

Satellites and oceanographic surveys provided data for environmental analysis (bathymetric depth, SST, Chlorophyll, mixed layer depth, wind velocity, current velocity, upwelling, sea surface height and estimates of gradients associated with these variables) which were included in a model to investigate how oceanography affects striped marlin distribution and behaviour.

Two oceanographic variables fishers are commonly interested in are SST and mixed layer depth. Median (or 'mid-point') SST was lowest during February and March, and highest during May, before dropping off again during June, July and August. Mixed layer depth was shallowest during January (median 20 meters) and gradually deepening through April (down to about 35 meters). Then from May through July, median mixed layer depth drops steeply to around 80m before becoming a bit shallower again in August. These trends are illustrated in Figure 11 below.

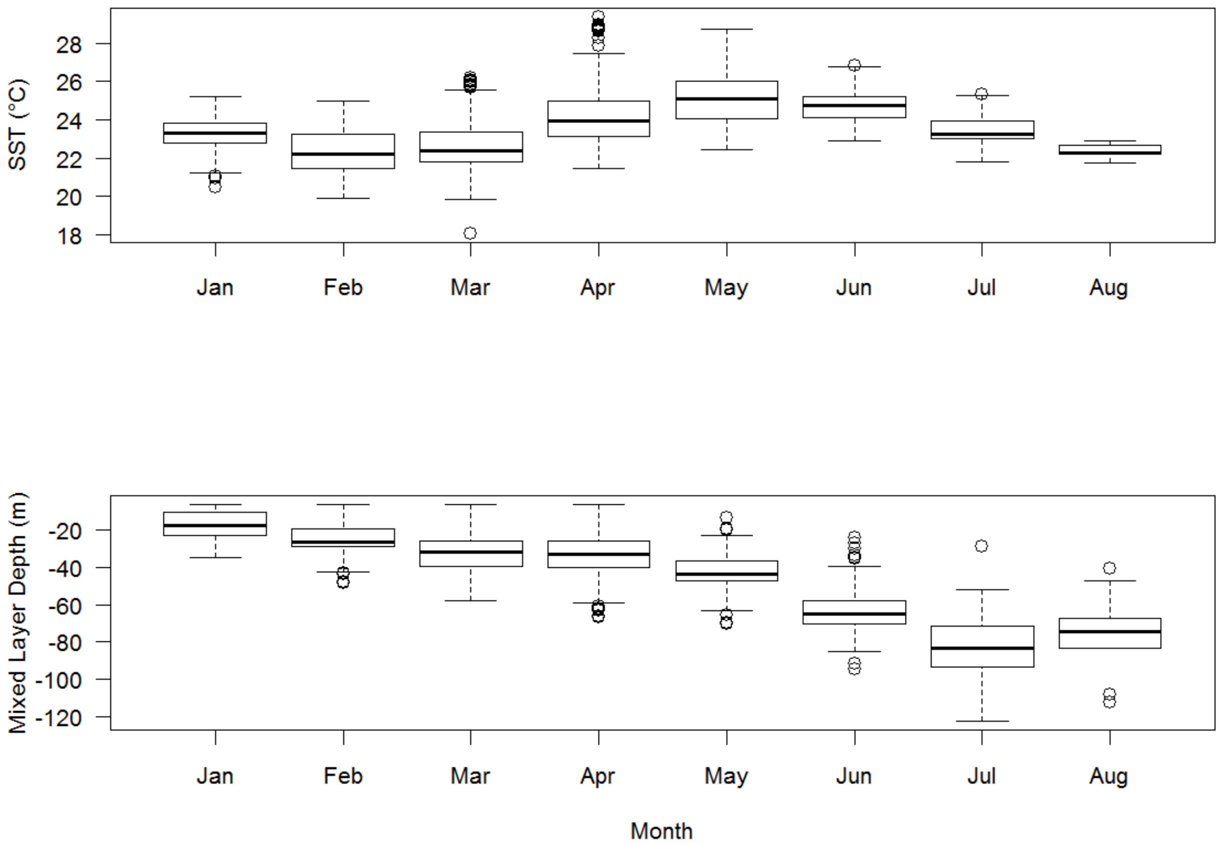

Figure 11. Distributions of two oceanographic variables (SST and Mixed Layer Depth) by month. For each month there is a white box with a black line inside. The most important part of each box is the thick black line, or the 'median' (or mid-point) value (ie. median mixed layer depth in January is 20 meters). The dotted bars and circles extended off the top and bottom of each box are basically 'extreme' values, also sometimes called 'outliers'.

Oceanographic gradients tend to be better predictors of habitat usage and behaviour than absolute values of any given variable. Gradients represent transitions where different water masses converge or diverge, and this process is important for nutrient cycles which drive food webs. Sea surface height (SSH) gradient (wave height) was one of the most consistently useful predictors, with models determining low sea surface heights to be generally preferred. Sea state affects the quality of data transmitted by tags, so increased sea height increases variation in location estimates, and this reduced location certainty could reduce the accuracy of behaviour estimates. Sea state can also be related to weather conditions, and poor weather might cause prey to disperse or change depth distributions. When building a predictive model we are looking for a few variables to explain most of the variation. In short, it is more straightforward to work with fewer variables than more variables.

Knowing that marlin, tunas, and sharks are apex predators at or near the top of the food web is helpful for understanding what is influencing their behaviour. In the open ocean, where they spend most of their time, the environment is often like a vast desert with sparsely distributed oases of food found at different times and locations. As nutrients cycle through the oceans, the convergence of certain conditions can promote pockets of high primary productivity (plankton), which can stimulate the food web. High prey concentrations nearby can go undetected because they are only aware of their immediate surroundings. Foraging success in the open ocean is dictated by chance, and the odds are not favorable most of the time. So most pelagic predators take opportunities as they present themselves, and this is why marlin stomachs can contain everything from pilchards, squid, penguins, to bottom fish. On the other hand, migration to rich summer feed grounds over the continental shelf of New Zealand may be hereditary or learned behaviour (or bit of both). In theory young fish that come to New Zealand which survive to breed may pass on this preference to the next generation.

Spawning is linked to the physiological state of the animal, and spawning aggregations are known for many animals like tunas and marlin to occur in discrete conditions (temperature, depth, geographic location, etc.). If we had data from spawning fish, it is likely that environmental data could be used to construct a useful predictive model.

There seems to be a degree of structure to striped marlin movement patterns in the southwest Pacific Ocean. Interestingly, more movement north and east from New Zealand into the central Pacific Ocean has been observed than into the western Tasman and Australian waters, and ongoing conventional tagging supports this. The Tasman Sea is known to be an oceanographically complex area, dominated by prevailing westerly conditions from Australia. Oceanographers consider the southwest Pacific Ocean to be one of the most poorly studied and understood oceanic systems in the world. Because the area is dotted by small countries and small economies (relative to America, Europe and Asia), the economic investment into basic oceanographic research in the region lags most of the rest of the world.

SUMMARY

The satellite tagging research program has had many successes and highlights, and leaves us with new questions too. Using methods specifically developed for this research program, the highest resolution satellite telemetry data possible have been collected from striped marlin. Those methods have drawn interest from overseas, and we look forward to seeing them utilized in other research programs. With these unique data, statistical models have been developed to estimate changes in behaviour through time and space. It is now possibe to estimate when and where a striped marlin stops to forage as they migrate through the vast Pacific Ocean. The ability to observe their behaviour with satellites also revealed a pattern of directional reversal in the tropics around 20°S latitude. This does not mean some ‘barrier’ exists there, or that striped marlin never cross this line, and other satellite tagging demonstrates this. However, the population is known to have a discontinuous distribution in the Pacific Ocean, with the western Pacific distribution being broken around the tropics and the eastern Pacific population is known to be continuous across the equator. So a behavioural mechanism which reflects the broader distribution of striped marlin on the corner of the globe may have uncovered in the research program. Several oceanographic variables seem to contribute to the pattern, but because the oceanographic knowledge in the southwest Pacific is poor relative to other systems like the California current, more work needs to be done. The satellite oceanography available to us is helpful, but we know much more can be revealed below the ocean’s surface.

Strong evidence that striped marlin movement and behaviour patterns are impacted by being captured and/or tagged emerged here. This is important to know because it impacts how trends in tagging data are interpreted. Knowing that there is probably some difference between the tagged and untagged populations influences our understanding of marlin movement. We can say that the timing of their movement cycles is probably effected by capture/tagging. They are still moving to areas they would normally be found, but possibly sooner than usual. Another important outcome is that tagging demonstrates high survivorship, and tag and release fishing is good. Fish handling is critical though, and treating animals well is extremely important to maximizing their chances of survival. Keeping their heads submerged below water during handling and reviving them behind the boat before release are simple, but very effective ways to ensure the health of the fish. Good tagging procedures are just as important. Placing tags properly minimizes harm to the fish and maximizes the chances of tags being returned later. A poorly placed tag is potentially wasteful, as it harms the fish by poking an unnecessary hole in it, and will likely lead to the tag falling out anyways. A small amount of extra effort to tag properly is worthwhile!

This work also demonstrates how striped marlin coveted by recreational fishers in New Zealand are vulnerable to fishing pressures throughout much of the Pacific Ocean due to their mobile nature. New Zealand’s fishery management doesn’t occur in isolation, and research such as this underscores both the need and requirement for coordinated multi-national management. This doesn’t mean countries dictating to one another how to manage their fisheries, rather it means working together to make sure everyone’s needs are met.

At the beginning of 2009 a scientific publication about the new methods developed for striped marlin satellite tagging was published in the journal *Marine Biology*. Two more scientific publications will be submitted in early 2010 about the behavioural modeling and oceanographic analysis discussed here as well. Some of the hallmarks of good science are peer reviewed publications contributing to broader understanding, and new questions being raised. The doors are wide open for more research to be done, and we are happy to say that this program has opened some of those doors!

ACKNOWLEDGMENTS

The contributions of many underpinned the ability for this research to happen. First and foremost, the New Zealand Marine Research Foundation has made this possible through funding and support of the New Zealand Big Game Fishing Council, its member clubs and individual members themselves. Many charitable trusts and businesses also contributed to the Foundation including the Lion Foundation, Green Thistle Trust, Pub Charity, Bay Trust, Whangamata Ocean Sports Club, Tauranga Game Fishing Club, Paslode International. Major charitable contributions were made by the Enterprise Motor Group which donated funding as well as vessel and crew time. In particular, tagging efforts in 2006 (which also rolled over into 2007 and 2008) were made possible largely due to Enterprise Motor Group Contributions. The Tagging of Pacific Pelagics (TOPP) program which is run largely out of Stanford University was a key partner and supporter during each phase of this research. We thank Professor Barbara Block in particular for her support. Massey University partnered with Blue Water Marine Research to initiate this research in 2003 and 2005. We thank our colleague, Professor Peter Davie for his expertise, input, experience, and inspiration during that period. Auckland University has financially and logistically supported the second half of this research from 2006-2009, and we thank Professor John Montgomery for facilitating that support. Different NZBGFC clubs have hosted the tagging team and its efforts including Tauranga Sport Fishing Club, Whangamata Sport Fishing Club, Whangarei Deep Sea Anglers Club, Houhora Game Fishing Club, Waihau Bay Game Fishing Club, and Te Kaha Sport Fishing Club. The expertise of captains of boats who hosted tagging efforts was excellent including Clyde Frazer of Brave Hart, Tom Francis of Ultimate Lady, Bill Marshall of Ubique, Bruce Going of Rona G, John Gregory of Prime Time, Pete Saul of Lady Jess, John Hamilton of Maverick, and Mark Dancaster of LeaRae. The anglers who generously donated their fish to the tag team significantly improved our tagging efficiency. A hearty thanks also to the ITM Fishing Show crew including Matt Watson and Graham MacKareth for their dedicated efforts for the program over several seasons.