NOTES FROM LECTURE BY PETER MORN - NIWA

Life, the universe, and all that: How do heavenly bodies influence aquatic organisms

The Shorter Oxford dictionary says a lunatic is someone affected with the intermittent insanity formerly attributed to changes in the phase of the moon. I believe it was the Romans who first coined the term: they were firmly of the view that mental instability peaked at the time of full moon. Many superstitions contain more than just a grain of truth, but why should the moon be associated with abnormal behaviour? After all, it's way up there, and we're way down here.

Well, perhaps the moon doesn't affect mankind, but it does play a role in the lives of other organisms in this watery world of ours. Starve, get eaten, fail to reproduce, and you've blown it! Life is tough out there! Succeeding at these tasks all depend on being in the right place at the right time. We use maps, watches and calendars to do this. Aquatic animals rely primarily on environmental cues. The name of the game **is** survival. Every animal wants enough sustenance to live comfortably. They want to be in a place that is relatively safe, and avoid places that are dangerous. They want to reproduce so that they have offspring in the next generation. So I will tell you how aquatic animals use the sun, moon, and stars to improve their chances of survival in our cruel world.

I will expound on two main aspects of the behaviour of marine animals: how they remain in a safe and sustaining home environment, and how they maximise their reproductive success.

First, how do they keep themselves safe?

Imagine you are a shrimp. You catch most of your food in the inshore waters only a few centimetres deep. But this is also where you yourself are most vulnerable to predation. Your refuge is offshore in deeper water; you need to know how to get there fast. So, to do this, every morning you look at the position of the rising sun in relation to the shore, and, using an internal biological clock that compensates for the changing position of the sun, you determine what direction you must move in to reach a safe depth offshore. How do we know that shrimp navigate using the sun? Well, shrimp were captured a couple of hours after sunrise and held in an arena that allowed them to see only the sky and sun. When they were threatened, with a quick flick of their aquadynamic telsons they would consistently move in an offshore direction. They maintain this ability generally until after the sun sets. However, animals captured at night, held in the same arena, and prevented from seeing the shore in daylight, moved randomly when threatened. They could see the sun but had forgotten where the shore was in relation to it. To test whether the shore or the sun was the most important stimuli, some deviant blighter shifted the position of the sun (it was all done with mirrors) and tested shrimp that had already learned the correct escape direction. In this situation, they escaped in a direction consistent with the sun's new position. So, when shrimp need to escape, learned solar cues are relied upon in the first instance. However, shrimp apparently don't have the best of memories. It was found that even if they had learnt the direction to the refuge, and then the sun was obscured for more than about 7 hours, then the correct escape response would have slipped from their tiny minds. On familiar shores, following the re-appearance of the sun, the escape response was rapidly re-learned. But if they were transported to an unfamiliar shoreline, it took them between 2½ and 4 hours to case the joint, determine the deep end and the shallow end, and orient in the new offshore direction. But clearly, if you are a shrimp, every morning it is important to see the sunrise, and relearn the escape route from the shore you are nearest to.

Sandhoppers, on the other hand, aren't sun-lovers. These amphipods tend to live under beach refuse above the high tide mark. They like to be moist, but not too wet or too dry. They also don't like to be eaten. Consequently, they tentatively emerge from cover in the evening, and move down the shore to forage. It has been shown that they also use celestial cues to navigate down the shore in the evening and then back to their refuges before sunrise. However, sandhoppers differ from shrimp in that their ability to use celestial orientation is genetically fixed, at least for juveniles. There is some evidence that as they get older, sandhoppers also get wiser, and can also use non-celestial cues, like local landmarks, to enhance navigational ability. But the genetically fixed celestial cues are the most important, and it has been shown that they cannot learn to navigate on a new shore. In an often cited experiment, which shows just how cruel biologists can be, groups of sandhoppers of the same species from the eastern and western shores of Italy were transposed. When the sun went down that night, both groups took their bearings from the sky and hopped the wrong way. They headed inland rather than down the beach. And because one night was not long enough to hop from the shore on one side of Italy to the shore on the other – sadly, they perished!

Most nudibranchs (also called sea slugs or sea hares) prefer to locomote while in contact with a firm substrate. However, some of you may have seen film of nudibranchs gracefully rippling their way through the water column propelled by the undulations of their mantle. And indeed, many sea slugs do spend time swimming at, or just beneath, the water's surface. For one investigated species, the swimming behaviour appeared to be a means of returning to deeper water if the mollusc found itself too close to the shore. It would swim to the surface, position its eyes either continuously or intermittently above the water line, and then swim in an off-shore direction. Even if all terrestrial landmarks were obscured from its vision, it would still swim off-shore. The researchers considered that the nudibranchs might be able to move in the right direction by simply swimming against any waves, rather than using visual cues. So to examine this hypothesis they re-tested animals which had, what they termed as, "disabled eyes". The visually challenged nudibranchs swam randomly, leading the researchers to conclude that a view of the sun was probably the most important cue enabling these creatures to swim in a desired direction.

Other aquatic organisms also exhibit solar cued navigation. Blue crabs (a sub-tidal species) have been observed resolutely swimming on the surface in a straight line away from the shore. Experiments have shown that if their view of the sun is obscured, they move randomly. Sand fiddler crabs (a semi-terrestrial burrowing species) have been shown to use celestial cues, terrestrial landmarks, substrate slope, and wave direction to facilitate a return to their burrows, although celestial cues were found to dominate all the others. Some turtles use the position of the sun for long distance migrations to beaches used for egg-laying. Again, this is done in conjunction with a biological clock that compensates for solar movement. A species of cricket living in banks adjacent to the sea frequently finds itself in the water, albeit accidentally. In swimming back to shore, the crickets rely primarily on celestial cues rather than any sighting of land. Celestial cues, particularly the sun, are obviously used as navigatory aids by many different groups of aquatic animals.

But the moon also appears to have an influence on the migratory behaviour and movement of some marine organisms. Talk to almost any commercial fisherman, and they will tell you how catches can fluctuate with the phase of the moon. [Although an analysis of recreational catch rates of snapper in the upper North Island found that less than 2% of the variation in catch per unit of effort over a 12 month period could be explained by moon phase.]

However, there are numerous documented examples of lunar synchronicity in the behaviour of fishes. Take, for example, a species of lanternfish in the North Atlantic. When the moon is new, they spend day and night in cold water deeper than 400 metres. But when the moon is full, at night they swim to the warmer surface waters, where they grow at a relatively fast rate. Perhaps, when there is a strongly moonlit sky, they are less prone to predation in the surface layers. Or maybe the food they prefer are abundant in the surface layers at this stage of the lunar cycle. Whatever the cause, this North Atlantic lanternfish has obviously found that, in the long run, it is beneficial for them to rise and greet the full moon. Yet, just a couple of thousand kilometres to the south, in the Tropical Atlantic, another closely related species of lanternfish exhibits a complete reversal of this pattern of behaviour. It grows fastest at the time of **new** moon, which is when it spends more time in the upper layers. Often, several species of lanternfish occur in the same body of water. They are all about the same size, have many similarities in diet, but exhibit subtle differences in patterns of vertical migration, which means that at certain times one or more of the species may be separate from the rest. Perhaps, by having a particular species synchronised to a particular part of the lunar cycle, the lanternfish are able to partition their environment so that each species gets a fair bite of the available plankton pie.

There are some behaviours by marine organisms, that are clearly linked to the lunar cycle, for which we have no explanation as yet. For example, poritid corals in the Caribbean cover themselves with thin mucous sheets. The mucus presumably protects the coral colonies from fouling during stressful environmental conditions, like an excess of suspended sediments after storms. The formation of these mucous sheets does not appear to be correlated with any of the measured environmental parameters, but it does have a lunar periodicity. Interestingly, though, different species of coral renew their mucous sheets at different times of the lunar cycle. The evolutionary advantages of having the protective sheet is obvious, but the reasons why different species have evolved to change their sheets at different, but regular, times can only be speculated upon.

The lunar cycle also appears to impart some stimulatory effects on the population size of plankton in some brackish African lakes. Despite relatively constant birth rates, plankton density fluctuated over one order of magnitude throughout the lunar cycle. The population increased exponentially through new moon and first quarter, till full moon, then suddenly decreased during the moon's last quarter. It was discovered that the cycle was induced by predation: a planktivorous fish was using a "moon trap" to decimate the plankton. An examination of gut contents showed that the fish cropped the plankton most efficiently when the full or nearly full moon rises just after sunset. After sunset, the plankton rise to the surface believing they will be safe in the cloak of darkness, but become suddenly visible and vulnerable in the first light of the rising moon. They are trapped in an illuminated expanse of water, and are consumed in quantity by the marauding fish. After the moon's last quarter, the plankton population has been ravaged, and the moon gives little light, so the fish shift to alternate foods and the surviving plankton get on with the job of making their populations grow exponentially again.

In that situation, the predator seems very much to have the measure of the prey. However, in other ecosystems the plankton have developed evasive tactics. One species, for example, can reduce the size of its body spines and surface area as full moon approaches, hence reducing its visibility and its appeal as a food item. Evolution is a dynamic process. Sometimes the predator has the advantage, sometimes the prey. But each is always trying to be one step ahead of the other.

Seabirds are known to migrate long distances over the featureless oceans. It appears that most rely for navigation on an in-built compass: they can actually sense the earth's magnetic field. However, there is also evidence that some species can recognise stellar configurations and use this information as a supplementary aid for navigation. For some seabirds, however, particularly the small petrel species, it appears to be important to watch the moon rather than the stars. It has been shown that on nights around full moon, these birds make less noise, spend less time in flight, and leave their nest burrows less frequently than on nights when the light intensity is low. It seems likely that the small birds are in a situation similar to the plankton: they are more vulnerable to predation on moonlit nights. So they have modified their behaviour to reduce their visibility, and hence, minimise their chances of becoming another animal's dinner.

So, a wide variety of aquatic organisms rely on having a view of the sun or the moon to keep themselves in familiar home environments, to help avoid predators, to find enough food, and to move from place to place.

In the second section of this talk, I will describe how some marine animals use celestial cues to maximise their reproductive success.

The cyclical nature of some astronomical phenomena provides an ideal means to co-ordinate reproductive activity. For most marine animals, being in the right place at the right time is absolutely crucial for successful reproduction, because most of them simply cast their sexual products into the water and rely on currents to bring male and female cells together. Given this methodology, your chances of reproducing are of course greatly enhanced if plenty of others of your species are around you, and if they're all thinking procreative thoughts too. Indeed, it has been demonstrated using mathematical modelling that, for a species using broadcast fertilisation, a synchronised cyclical reproductive system markedly reduces the probability of extinction of the population, relative to a non-cyclic system.

The moon is the most frequently reported reproduction synchroniser, but cues from the sun, in the form of changing day length, have also been noted. It is **not** surprising to find annually spawning, shallow-dwelling animals using day length as a procreative cue. For example, some species of starfish, when held in a laboratory under a photoperiod regime 6 months out of phase, spawned 6 months out of phase relative to individuals in the field or laboratory experiencing normal celestial photoperiods.

However, it possibly **is** surprising to find that for our own orange roughy, that ugly fish of the deep, day length is probably the critical factor in determining when spawning occurs.

Spawning by this fish on the Challenger Plateau to the west of New Zealand is highly consistent from year to year, occurring in a period of approximately 8 days in early July. Despite the fact that this activity takes place at depths of 800 to 1200 metres where light intensity to our eyes would be virtually pitch black, day length is the only measured environmental parameter that was found to be consistent over all years. So even at those depths, it appears that orange roughy know how long the day is, and hence, know whether or not it is time to school up and produce more export product for New Zealand's fishing industry.

Lunar synchrony of reproduction by marine animals is an almost universal phenomenon – well, at least it is in our little bit of the universe anyway. It has been reported for marine molluscs, polychaete worms, starfish and sea urchins, corals, and reef fish. Different groups or species of animals appear to have synchronised with different parts of the lunar cycle, but spawning activity of most groups tends to be concentrated in the few days around new and full moon. Methods of reproduction are many and varied. Some species, like the polychaete worm *Platynereis megalops*, have developed an obsolutely unique copulatory process which circumvents some of the problems associated with broadcast fertilisation. This activity always takes place in July, two nights after full moon, about 55 minutes after sunset. The eggs of this species are unfertilizable after 40 seconds of contact with seawater. So when the lunar and solar cues indicate that time is right, all the *Platynereis* worms swim to the surface. On contacting a female, the male wraps his body around hers, inserts his anus into her mouth and goes into a general contraction of the body muscles. Since in both sexes the gut wall is already degenerate, sperm pass from the male's anus directly into the coelom of the female, where the eggs are fertilised and spawned almost immediately via the female anus. Both parents die after this performance. Exhausting stuff! Strange are the ways of nature!

But for most marine organisms with lunar synchronised reproductive cycles, the performance is relatively straightforward. Take, for example, the purple sea urchin. This species spawns each year over a period of about 3 months. Maturation of the gonad appears to be stimulated by increasing day length. Although the spawning season is relatively long, the actual release of reproductive products always occurs on nights when the moon is at, or very near, its full phase. So the urchins might spawn on 3 or 4 nights around each full moon, in each of the 3 to 4 lunar cycles of the spawning period. In doing this, they are putting their reproductive eggs into several baskets, but at the same time, maximising the quantity of reproductive products in the water at any one time.

I will digress here a little bit and talk about plants! To many zoologists, plants are simply green things that animals eat, whether they are terrestrial or aquatic. But the plant I wish to mention is not green. It is the brown alga, *Fucus vesiculosus*, which occurs in the Baltic Sea. Marine plants have problems that terrestrial ones don't: they can't rely on the birds and bees to do their fertilisation for them. So, like many of the marine invertebrates and fishes in that same watery environment, they rely on broadcast fertilisation. And in doing this, they have evolved exactly the same techniques to ensure maximum reproductive success with minimal energy outlay. Although the brown alga can release eggs at any time on any day, it was found that there were distinct peaks in the release of reproductive products. The peaks occurred between 6 and 10 p.m., two days before new and full moon. Reproductive activity was found to have no correlation with temperature, or with water level. So the brown alga, like many species of aquatic animal, have derived great adaptive value by co-ordinating gamete release from male and female individuals. It is perhaps interesting to wonder, though, just what mechanism the plants use to determine that it is between 6 and 10 p.m. on a particular day of the lunar cycle. I guess there's no reason why they can't use light receptors to tell the time. After all, some terrestrial plants have leaves that can track the path of the sun.

I have mentioned already why reproductive synchrony is useful, and maybe even essential, for breeding success if you use the broadcast spawning technique. However, being synchronised has another advantage. If all the organisms around you (of either the same or different species) are producing a myriad of microscopic young, then the chance of any individual offspring being consumed by a predator is much reduced. The predators will race around gobbling up as much of this high energy soup as they can, but they soon become satiated, and have to leave lots of the soup to grow and mature. Salmon also employ a similar technique. Young salmon in fresh water produce a thyroid hormone just prior to their seaward migration. The hormone initiates migration and is essential for survival in salt water. Concentrations of the hormone peak at new moon, ensuring that salmon smolt migrate together in waves, hence minimising the predation risk on individual fish.

However, predators also have developed means to maximise the survival of their own young by taking advantage of these cyclical peaks in prey abundance. For example, some planktivorous reef and lake fish spawn at a time that ensures their larvae hatch around the time of new or full moon. Planktonic food is then plentiful. Some reef fish have an added incentive to synchronise their reproduction to the lunar cycle. These are the fish that produce small numbers of eggs and care for them, rather than producing large numbers of eggs that are dispersed by the currents. Eggs are laid, stuck to the substrate, and fertilised just prior to the full moon. The extra light at this time allows the concerned parent to better guard the eggs from predators. Egg maturation is quick, and the larvae hatch just after full moon, in time to feast on the high energy clouds of reproductive material being produced by the various fervently procreating invertebrates in the neighbourhood.

So, using a wide assortment of examples from raw life, I have demonstrated how marine organisms use celestial bodies as their watch, their calendar, and their compass. In doing this, they can synchronise their reproductive activities to maximise the chances of their genes making it to the next generation by ensuring a high rate of egg fertilisation, a reduced probability of juvenile mortality, and a ready supply of high-energy food for the developing young. I have also shown how, using celestial bodies again, they can remain in their most preferred habitat, where they are relatively safe and well fed.

This is, logically, the end of this talk. However, I would like, just briefly, to emerge from the salty ocean, and spare a final thought for good old *Homo sapiens*. I began this presentation by mentioning lunatics, and the strange effects the Romans believed the moon had on human mental stability. I suggested that there is a grain of truth in every superstition. Well, while searching for information to include in this talk I found, in an obscure publication, a report on what the authors described as a "peculiar biological phenomenon". Behavioural observations of some fish, prawns and crabs showed their appetites to accelerate during times of new and full moon. Cyclic fluctuations in the hormone balance in their blood were detected throughout the lunar cycle. The authors postulated that the gravitational forces of the moon could influence hormone levels in marine animals. Could the moon really effect the biochemical balance in living organisms, including humanity? Maybe.