

Early warning systems to minimize the risk of box jellyfish stings by empowering stakeholders

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Supported by the Australian Government's
National Environmental Science Program
Project 2.2.3 Early warning systems to minimize the risk of box jellyfish stings by empowering stakeholders

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National Library of Australia Cataloguing-in-Publication entry:
978-1-925514-29-2

This report should be cited as:

Condie, S. A., Gershwin, L. A., Kingsford, M. J., Pitt, K. A., Richardson, A. J. and Thomas, L. (2018) *Early warning systems to minimize the risk of box jellyfish stings by empowering stakeholders*. Report to the National Environmental Science Program. Reef and Rainforest Research Centre Limited, Cairns (44pp.).

Published by the Reef and Rainforest Research Centre on behalf of the Australian Government's National Environmental Science Program (NESP) Tropical Water Quality (TWQ) Hub.

The Tropical Water Quality Hub is part of the Australian Government's National Environmental Science Program and is administered by the Reef and Rainforest Research Centre Limited (RRRC). The NESP TWQ Hub addresses water quality and coastal management in the World Heritage listed Great Barrier Reef, its catchments and other tropical waters, through the generation and transfer of world-class research and shared knowledge.

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Cover photographs:

The first known Irukandji jellyfish, *Carukia barnesi*, periodically infests North Queensland beaches and reefs. Its sting produces life-threatening illness in its victims (© Lisa Gershwin).

The presence of Irukandji jellyfish often leads to beach closures in North Queensland (© Scott Condie).

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ACRONYMS

AIC	Akaike Information Criterion
AMPTO	Association of Marine Tourism Operators
AVJD	Australian Venomous Jellyfish Database
GBR	Great Barrier Reef
GLM	Generalised Linear Model
LMM	Linear Mixed Model
NESP	National Environmental Science Program
QAS	Queensland Ambulance Service
SLSQ	Surf Life Saving Queensland
SOI	Southern Oscillation Index

ACKNOWLEDGEMENTS

Our thanks to the following contributors.

Gavin Singleton of the Yirrganydji people and the Yirrganydji Indigenous Land and Sea Rangers provided advice and assistance with field programs.

Paris Hansch (Griffith University) worked up data from stinger cams toward her Masters Minor Project: *“The influence of physical factors on the presence and abundance of cubozoan jellyfish”*.

Dr John Andrewartha (CSIRO) calculated the tidal heights used in the statistical analysis.

Associate Professor Jamie Seymour (James Cook University) provided Irukandji polyps for the laboratory sensitivity experiments.

EXECUTIVE SUMMARY

Venomous jellyfish, including Irukandji and box jellyfish, commonly occur on the Great Barrier Reef, where stings result in many hospitalisations each year. The aim of this study was to help minimise the risk of future stings by empowering stakeholders with the information and understanding needed to implement an early warning system.

The first step was development of a database, referred to as the Australian Venomous Jellyfish Database (AVJD), that combines relevant information from existing sting datasets, hospital records, surf lifesaving records and research data. This supported development of statistical models that relate sting data to environmental conditions and thereby form the basis for forecasting models covering stinger hotspots on the Great Barrier Reef. Wind direction was found to be the most important predictor, with most areas having greater stings during north-westerly winds and fewer stings during south-easterly winds. Slow wind speeds and incoming tides also led to more Irukandji stings for Cairns Beaches, Cairns Islands, and Townsville Beaches. Tidal height seemed to be important in all areas, except Whitsundays Beaches, with more stings at low tide.

The sensitivity of Irukandji to other potential environmental drivers was tested using laboratory experiments, which indicated that Irukandji polyps are insensitive to pesticides, whereas their productivity was reduced by the higher water temperatures and lower pH levels expected on the GBR by the end of the century. Improved monitoring and identification techniques were also developed with the assistance of project partners such as the Yirrganydji Indigenous Land and Sea Ranger Program and Surf Life Saving Queensland.

It is recommended that the models continue to be improved through sustained monitoring, data collation and targeted sensitivity studies. In regions with satisfactory data coverage and predictability, such as Cairns beaches, pilot forecasting systems should be operationalised as soon as practicable. This will help empower Traditional Owners, life-savers, tourism operators, and the public to reduce stinger impacts on the Great Barrier Reef.

1.0 INTRODUCTION

Irukandji are small transparent jellyfish that cause the potentially fatal Irukandji syndrome. This syndrome can result in debilitating illness, involving excruciating pain, sweating, nausea and vomiting, with the most severe cases experiencing acute heart failure, pulmonary oedema and even death. Because Irukandji are small and do not always leave obvious marks on the body, many stings remain undiagnosed.

Irukandji stings are a leading occupational health and safety issue for marine industries throughout tropical Australia and an emerging problem elsewhere in the Indo-Pacific and Caribbean. In Queensland, venomous jellyfish cause hundreds of hospitalisations annually and can have a major impact on tourism. Beach closures are common and cancelled tourism bookings following two fatalities on the Great Barrier Reef (GBR) in 2002 were estimated to have cost in excess of \$65M. The tourism industry reports that Irukandji are the number two reason Australians are taking their tourism dollars overseas.

Stakeholders need accurate and rapid information on the presence of Irukandji to develop mitigation strategies, such as changing the location of tourism activities, varying the timing of immersion while diving or swimming, or wearing protective garments.

Predicting the risk of Irukandji outbreaks requires an understanding of how they respond to environmental conditions, including water quality, and meteorological and oceanographic conditions. There is evidence that physical factors, such as salinity, temperature and wind can influence abundance (Gershwin et al. 2013, 2014; Llewellyn et al. 2016; Mooney and Kingsford 2016). Anecdotal accounts from lifeguards and other beach-users over many years raised the hypothesis that stings coincide with periods of weak north-easterly winds. Gershwin et al. (2014) tested this hypothesis for one beach (Palm Cove) on the Great Barrier Reef in Far North Queensland. Using collated records of stings and local wind, they found that blooms largely coincided with relaxation of the prevailing south-easterly trade winds on the day prior to the sting.

The aim of the current study was to assess the feasibility of an early warning system to forecast the relative risk of Irukandji stings across different regions of the GBR, and develop the models to underpin such a system. This required a number of key project elements:

- (i) Collation of existing data on Irukandji observations and stings across the beaches, offshore islands and reefs of the GBR, through development of an Australian Venomous Jellyfish Database (AVJD).
- (ii) Identification of other potential environmental drivers by exposing Irukandji to a range of water quality conditions in laboratory experiments.
- (iii) Refinement of methods to observe and accurately identify Irukandji species to help support ongoing refinement of Irukandji prediction.
- (iv) Analyses to relationships between the presence of Irukandji and local environmental conditions, particularly winds and tides.
- (v) Engagement with key Indigenous and stakeholder groups as likely contributors and users of a forecasting system.

This report describes significant advances across all of these elements and makes recommendations for future developments.

2.0 METHODOLOGY

The project consisted of multiple strands of research all aimed at developing the methodologies and tools necessary to create and continuously improve a jellyfish forecasting system for the GBR. This included Indigenous and stakeholder engagement, development of a jellyfish database, improved techniques for detection and identification, laboratory work on environmental sensitivity, and developing statistical relationships between the risk of stings and environmental factors.

2.1 Engagement

Prior to the start of the project, planning began with a workshop involving Traditional Owners and key stakeholders such as the Association of Marine Park Tourism Operators (AMPTO), Surf Life Saving Queensland (SLSQ), and Queensland Ambulance Service (QAS). This engagement has continued throughout the project, particularly through collaboration on field and laboratory investigations with Indigenous groups and SLSQ.

The project involved extensive engagement with Gavin Singleton of the Yirrganydji people, and the Yirrganydji Indigenous Land and Sea Ranger Program (<https://www.youtube.com/watch?v=elAWJiHAKVY>). Rangers were briefed on the project and trained in the use of camera systems for detection and identification of jellyfishes. They also assisted with trials to test other equipment and to obtain abundance estimates for Irukandji and other jellyfish around Palm Cove. While some of these activities were curtailed by the presence large crocodiles and associated beach closures, they were very effective in raising the profile of the project within the Cairns community.

An Indigenous undergraduate student at Griffith University, Tish King, also contributed to the project through a summer research project. With financial support via a Kungullanji Indigenous Summer Research scholarship (administered by the Gumurrii Student Support Unit at Griffith University), Tish completed experiments on the effects of salinity on polyps of the Irukandji jellyfish *Carukia barnesi*.

2.2 The Australian Venomous Jellyfish Database (AVJD)

One of the primary goals of the study was development of an Australian Venomous Jellyfish Database (AVJD). This is an oracle database hosted at the CSIRO Oceans & Atmosphere laboratories in Hobart, with public components of the database also hosted through eAtlas (<https://eatlas.org.au/data/uuid/09311b48-e6f1-484f-945b-8a5b5bfba232>).

Data in the AVJD have come from many different sources and are intended to serve the needs of the medical, scientific, safety, and media communities, as well as interested members of the public. Medical practitioners and safety personnel have contributed data from cases they treated; beach managers have contributed data obtained through their local communities; and scientific researchers have contributed data obtained through established reporting systems and systematic searching of media and online search engines.

Each data record represents one de-identified sting case or one or more specimens collected or photographed, and contains a unique numerical identifier. Wording from the original source has been preserved insofar as practical. At a minimum, sting records contain the locality, date, envenomation type (box or Irukandji), general habitat (beach, island, or reef), and data source. Most sting records contain time of day, age and gender of the victim, and a free-text notes field (Appendix 1). Where known, records contain where the sting occurred on the body, whether the person was wearing protective clothing, and details that may be useful in diagnosing species including signs, symptoms and severity (e.g., stable, critical). Metadata have been added to facilitate comparisons, including region, state, habitat (beach, reef, or island), and body region (head, trunk, upper limb, lower limb). One or more sources of information pertaining to each record are noted in the source field: internet URLs, newspaper references, or other literature references are provided when available.

Most of the data included in this database derive from and are validated by one or more Internet URLs, Proquest references, or peer reviewed publications. A smaller number of cases were given to us by other sources, such as hospitals, ambulance officers, safety personnel, or victims, and are indicated as such. Records have been verified using expert knowledge to review the reliability of the information source and factors such as reported symptoms, to ensure that they relate to legitimate Irukandji or *Chironex* stings or specimens.

Records have been entered into the database individually, and cross-checked to ensure that they are not duplicated. Record uniqueness has been determined primarily on a combination of five criteria: locality, date, time, age, and gender. If a question of duplication has arisen, a conservative approach has been employed, with only one record made public.

Data currently uploaded for public access were previously publicly available through mainstream media or peer-reviewed publication. This database contains 1268 records and has been made freely available through eAtlas (<https://eatlas.org.au/data/uuid/09311b48-e6f1-484f-945b-8a5b5bfba232>). Appendix 1 lists the public data fields.

More stings are also collated in a larger, non-public version of the database, for which we are seeking formal permission from the data owners to make public. These include sting data from hospitals, regional medical centres, ambulance services, and air evacuation services. In all, the whole (published and unpublished) database currently contains more than 2300 stings and 84 specimen records. We will continue to upload more data as permissions are granted and we hope that the existence of the database will inspire others to contribute their data.

2.3 Irukandji sensitivity to water quality – laboratory studies

While there is increasing evidence that meteorological and oceanographic conditions influence Irukandji, effects of common water quality stressors such as nutrients, pesticides and CO₂ pollution (ocean warming and acidification) have not previously been considered for either early lifecycle polyps or later stage medusae.

Two experiments on the effects of water quality on Irukandji polyps have been completed as part of the current study. Because Irukandji polyps are cryptic and have never been located in the field, they were sourced from medusae collected near Double Island on the GBR (courtesy

of Associate Professor Jamie Seymour, James Cook University). The first experiment tested responses of polyps of *Malo maxima* to two common pesticides found in the GBR lagoon. The second tested effects of CO₂ pollution (namely ocean warming and acidification) on polyps of *Carukia barnesi*. A third experiment is currently testing the interactive effects of salinity and pesticides on polyps of *C. barnesi* and will be reported in the future.

2.3.1 Sensitivity to pesticides

Two pesticides commonly detected in the GBR lagoon are the photosystem II herbicides Atrazine and the nicotinoid insecticide Imidacloprid. Although pesticides are formulated to target specific organisms, non-target organisms are often impacted (Pisa et al. 2015). Indeed herbicides, designed to target plants, can detrimentally affect aquatic invertebrates (Bejarano & Chandler 2003), and neonicotinoid insecticides can affect aquatic invertebrates that have central nervous systems (Krieger 2010).

Concentrations of pesticides vary spatially and temporally and may spike following heavy rainfall. Studies of the effects of pesticides frequently assess responses to individual pesticides, despite multiple pesticides co-occurring and potentially causing additive or synergistic impacts (the so-called “cocktail effect”). We were interested, therefore, in testing the effects of exposing Irukandji polyps to Atrazine and Imidacloprid, both individually and in combination. The Irukandji species selected was *Malo maxima*, a species reported to cause severe Irukandji syndrome (Gershwin et al. 2013). We tested the hypothesis that polyps of *Malo maxima* exposed to Imidacloprid and Atrazine, both individually and concurrently, would exhibit reduced asexual reproduction, impaired mobility and impaired feeding ability, and that the effects would be more severe when exposed to both pesticides concurrently.

The experiment consisted of two orthogonal factors: Imidacloprid and Atrazine. Polyps of *M. maxima* were exposed to three levels of Imidacloprid (High: 200 ngL⁻¹, Low: 2 ngL⁻¹, Control: 0 ngL⁻¹) and Atrazine (High: 20 000 ngL⁻¹, Low: 200 ngL⁻¹, Control: 0 ngL⁻¹). High concentrations were chosen to reflect those recorded in the catchment area or inshore waters of the GBR during flood events (Gallen 2014). The low concentrations reflected those recorded during non-flood periods. Five replicates were randomly allocated to each treatment (9 treatments total).

The experiment was done in a controlled temperature laboratory maintained at 26°C. Diel changes in light were mimicked during the acclimation period and experiment. The seawater used in the experiments was collected from the Gold Coast Seaway, Queensland. Water was filtered twice with a 100-µm mesh before use. Seawater pH (7.9 - 8.0) and salinity (33 ppm) were measured daily with a multi-parameter sensor (YSI ProPlus). Salinity was manipulated, as required, by diluting seawater with reverse osmosis water.

Replicates consisted of 20 ml glass dishes containing 5 polyps and polyps were fed every fourth day with newly hatched *Artemia* nauplii. The experiment ran for 33 days and the number of swimming polyps and settled polyps per beaker was recorded every fourth day.

A feeding assay was used to measure the feeding ability of the polyps at the end of the experiment. Four polyps from each replicate were transferred into the wells of a 96 well plate (1 polyp per well) to assess their feeding behaviour. Polyps were left to acclimate for ~ 2 hours.

A number of brine shrimp were then introduced into the wells (8-15 brine shrimp per well) and polyps were allowed to feed for 20 minutes, after which the number of consumed, dead, and/or alive brine shrimps was recorded.

To quantify the mobility of attached (i.e. non-swimming) polyps, polyps from each replicate were filmed at the start and end of the experiment with a camera attached to the microscope (Digitech Computer, QC-3199). The percentage mobility (defined as the percentage of changed pixels of the detected subject between the current sample and the previous sample (Grieco et al. 2013), was calculated as:

$$\text{percentage mobility} = \frac{100 \times CA_n}{A_{n-1} + A_n}$$

where CA_n is the number of changed pixels between previous and current samples; A_{n-1} is the number of pixels in the previous sample and A_n is the number of pixels in the current sample. All data were checked for normality with standardised residuals and Q-Q plots; and were log (x) or log (x+1) transformed when necessary to improve normality and homogeneity of variance assumptions. All analyses were carried out in SPSS (IBM SPSS statistics, ver. 22).

We performed three separate statistical analyses. In the first analysis, the total number of polyps was analysed using repeated measures linear mixed models (LMMs). The fixed factors for the analysis were: Atrazine concentration (3 levels: High, Low, Control), Imidacloprid concentration (3 levels: High, Low, Control) and Day (9 levels: every 4 days from Day 1 to Day 33), which was the repeated measure. Different models were examined (AR(1), AR(1) heterogeneous, compound symmetry), and the best-of-fit model was selected by comparing model selection criteria (-2 log likelihood, Akaike's Information Criterion (AIC), Bayesian Criterion (BIC)).

The second statistical analysis was investigating feeding assay with LMMs, with Imidacloprid and Atrazine again as the two fixed factors. Four polyps from each replicate were used for the feeding assay. The last statistical analysis was investigating the mobility of polyps using LMMs. The three fixed factors were: Atrazine, Imidacloprid, and Day.

A post-hoc power analysis for asexual reproduction was done using G* Power (Version 3.1.9.2) to calculate the number of replicates that would have been required to detect a significant difference among treatments, had one occurred, on the last day of the experiment.

2.3.2 Sensitivity to pCO_2 and ocean warming

Anthropogenic CO_2 is lowering the pH and warming the ocean. Understanding whether polyps of Irukandji jellyfish tolerate changing water chemistry and temperature is critical for assessing whether the risk posed by Irukandji populations will change. Ocean pH and temperature are changing concurrently, so it is necessary to analyse the potential interactive effects of these stressors. The Irukandji species *Alatina alata* tolerates the temperature and pH conditions predicted for the end-of-century (Klein et al. 2014), but effects of climate stressors on *Carukia barnesi*, the Irukandji species responsible for many severe stings (Gershwin et al. 2013), has not been studied. Moreover, because other Irukandji taxa appear tolerant of changing water chemistry (Klein et al. 2014; 2017; Angulo-Chinas 2017), we were interested in studying potential sub-lethal as well as lethal effects. This study investigated the potential interactive

effects of warming and acidification on the productivity, respiration, metabolome and behaviour of polyps of *Carukia barnesi*.

Three pH levels (8.0, 7.9 and 7.7) and two temperature levels (26°C and 28°C) were tested using an orthogonal design. The pH levels were chosen to represent current (8.0), probable (7.9) and extreme (7.7) end-of-century predictions for changes in pH. CO₂ concentrations were manipulated using a series of mass-flow controllers (see Klein et al. 2017) and temperature was manipulated using water baths. Eight replicates were assigned to each treatment. The experiment ran for 11 days and the number of swimming polyps produced and the rate of respiration of polyps was measured every three days. Respiration rates were measured using microrespiration vials fitted with dissolved oxygen optodes. Polyps were filmed at the beginning and end of the experiment and movements of polyps (an indication of behaviour) were analysed using image analysis software (Ethovision). At the end of the experiment, polyps from all treatments were harvested and preserved for metabolomic analysis. Metabolomes are still being analysed and results are not yet available.

2.4 Improved techniques for detection and identification of Irukandji

To determine if underwater cameras can detect Irukandji and other cubozoans, new camera monitoring and identification systems were trialled over the 2016-17 and 2017-18 Irukandji seasons. Camera systems, known as JellyCams (Llewellyn et al. 2016), were deployed at Yorkeys Knob, north of Cairns (Figure 1A) and at the fishing pier on the Strand in Townsville (Figure 1B). Multiple sets of low-cost GoPro® cameras configured with underwater LED lights were also deployed at Magnetic Island near Townsville (Figure 1C). These systems are referred to here as IrukandjiCams.

More traditional sampling was also undertaken in the 2017-18 season, involving twice daily net sampling over a 17-day period at Palm Cove. When Irukandji are sampled using this technique, accurate identification is a critical step in establishing reliable data on distributions. However, this type of sampling is most commonly undertaken by non-experts with limited training. To help improve accuracy, a number of jellyfish viewing chambers were designed and constructed for use by stakeholders such as SLSQ (Figure 2). These systems allow anyone conducting sampling operations to take high resolution images using a smartphone, that can subsequently be identified by jellyfish experts. The chambers were distributed to Indigenous rangers and SLSQ in Cairns and Townsville.

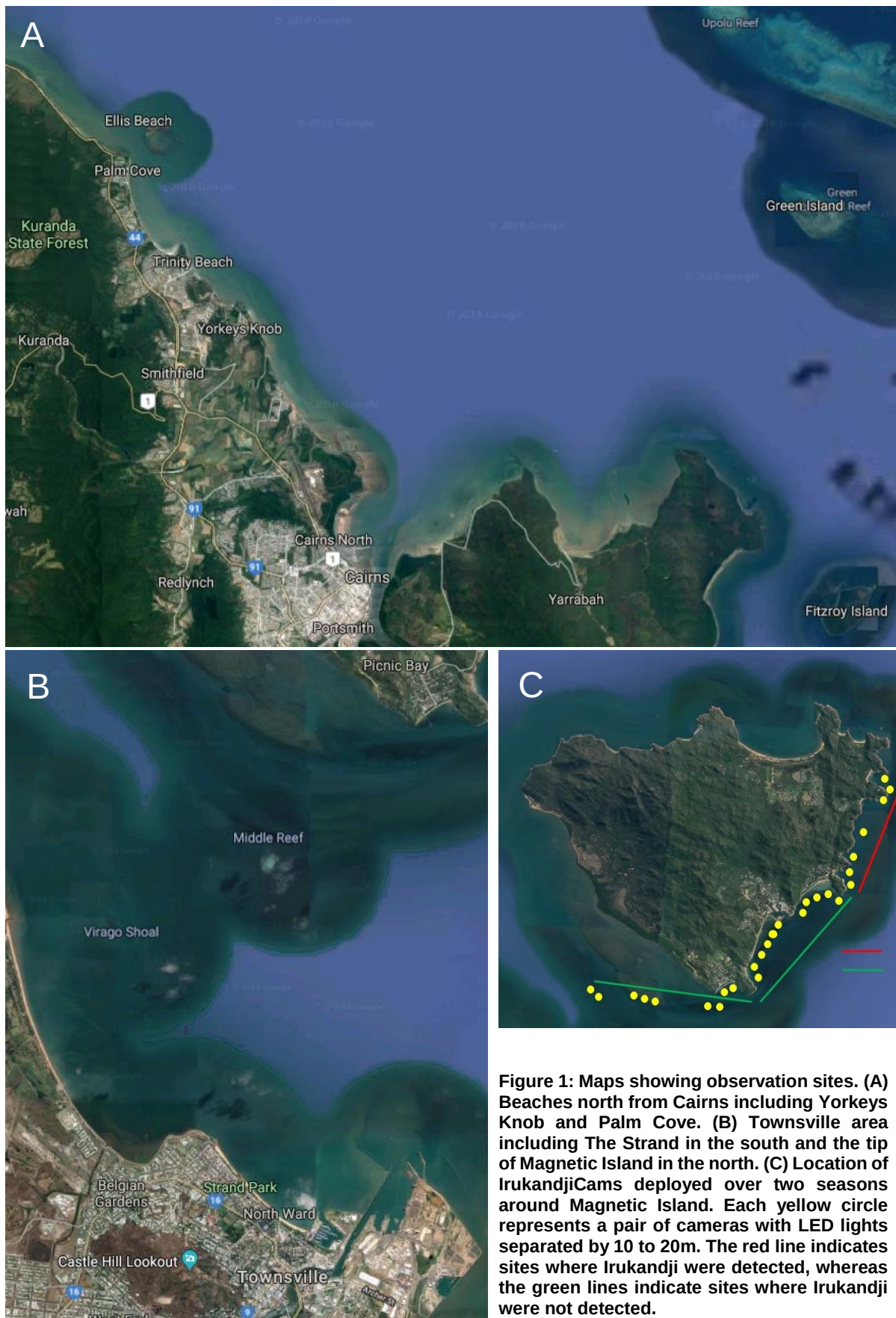


Figure 1: Maps showing observation sites. (A) Beaches north from Cairns including Yorkeys Knob and Palm Cove. **(B)** Townsville area including The Strand in the south and the tip of Magnetic Island in the north. **(C)** Location of IrukandjiCams deployed over two seasons around Magnetic Island. Each yellow circle represents a pair of cameras with LED lights separated by 10 to 20m. The red line indicates sites where Irukandji were detected, whereas the green lines indicate sites where Irukandji were not detected.



Figure 2: Viewing chambers provided to stakeholders to improve the quality of images submitted for identification by experts. (A) Transparent sides and front provide strong lighting to photograph specimens and the black background enhances the contrast of specimens. (B) Low-cost perspex design in which a petri dish is mounted between LEDs (powered by a 9v battery). A smartphone rests on the upper perspex sheet (focusing through the large slit), which also contains magnification lenses (the smaller holes).

2.5 Relationships between environmental conditions and Irukandji

2.5.1 Sting and environmental data

Data from the AVJD was used to identify relationships between the presence of Irukandji and local environmental conditions. To ensure consistent data with sufficient spatial and temporal coverage, the analysis used only sting data from 1985-2016 between latitudes 14°S and 22°S. This excluded 227 stings recorded over the previous 90-years and 36 stings recorded outside of the region. This left a total of 1,071 stings for analysis (last updated on 2 August 2018). Key data fields used in the analysis provided spatial information (Latitude, Longitude, and Area – Beach, Island or Reef) and temporal information (Date, Time-of-day) for individual sting events.

The key environmental datasets used in the analysis were modelled winds and tides. Estimates of daily averaged wind-speed and wind-direction were obtained from the European Reanalysis (ERA-Interim) model produced by the European Centre for Medium-Range Weather Forecasts (Dee et al. 2011). Although this is a large-scale global wind product, modelled winds off Cairns are consistent with those recorded at Cairns airport (Gershwin et al. 2014). Wind-speed and wind-direction were extracted every 0.75° of latitude down the coast and assigned to the closest region; the three major regions in the analysis are around Cairns, Townsville and the Whitsundays. Hourly tidal elevation was estimated for seven stations along the GBR (Albany Island, Cairns, Cardwell, Cooktown, Fife Island, Cape Grenville and Townsville) using local harmonic constants and the XTide software (<https://flaterco.com/xtide/>). The closest tide station was used for each region in the analysis.

2.5.2 Statistical models

Irukandji stings were modelled using a generalised linear model (GLM). A GLM generalises ordinary linear regression by allowing the linear model to be related to the response variable via a link function and by allowing the magnitude of the variance of each measurement to be a function of its predicted value (McCullagh & Nelder 1989). For each region, we used a GLM with the number of Irukandji stings per day as the response variable. The GLM had a Poisson error structure and a log link function (Crawley 2005). There was reasonably consistent sampling effort in the database since 1985 (more sporadic prior to this date) and so we inferred absences when stings were not recorded in the data for a day. Because Irukandji occur irregularly through time, the database will inevitably miss some isolated sting events. However, we can generally be confident of capturing larger infestations.

We included six predictors in the models: Month, two wind variables, and three tidal variables. Unfortunately, persistent cloud cover excluded the use of sea surface temperature as a predictor. Month was a factor and arranged so that the summer was in the middle of the year (i.e., from June to May). The two wind variables were Speed and Direction. For each day within each region (Cairns, Townsville or Whitsundays), hourly wind-speed and direction was used. We derived cumulative wind Speed and Direction, working backwards from each day, with the current day being Day 1. We calculated cumulative winds from the current day (Day 1) to 14 days previously for every day in every Region and Area. To provide greater weighting for winds on more recent days, we used an inverse weighting for each day, where the weighting was given by $\frac{1}{i}$ for each day i . Thus, the Cumulative Speed for n days was given by:

$$\text{Cumulative Speed}_n = \frac{\sum_{i=1}^n \frac{\text{Speed}_i}{i}}{\sum_{i=1}^n \frac{1}{i}}$$

For example, calculations for the 3-day cumulative wind speed are:

$$\frac{\frac{1}{1} \times \text{Wind Day 1} + \frac{1}{2} \times \text{Wind Day 2} + \frac{1}{3} \times \text{Wind Day 3}}{\frac{1}{1} + \frac{1}{2} + \frac{1}{3}}$$

Similarly, we calculated the cumulative weighted wind Direction using the formula:

$$\text{Cumulative Direction}_n = \frac{\sum_{i=1}^n \frac{\text{Direction}_i}{i}}{\sum_{i=1}^n \frac{1}{i}}$$

We used circular statistics in the R Package Circular to calculate the weighted cumulative mean, because direction 0° is the same as 360°. We initially used a smoother for this term in the model, but because of its non-linearity and the lack of winds of all directions, we found that it was better to use wind Direction as a factor with four levels (NW, NE, SE and SW). In some Regions and Areas, not all wind Directions were present.

To assign each event to the tidal cycle, we used tidal data from the closest of the seven stations to calculate three tidal variables: (i) the tidal range each day (m); (ii) the tidal height (m); and

(iii) whether the tide was incoming or outgoing. To estimate the three tidal variables, the time of day of the event was required. However, the Time of Day was only available for 780 observations, and the 291 missing observations were estimated assuming a random Time of Day, which will not influence the relationship but will keep these rows in the analysis. Tidal range was not significant in any models and will not be considered further.

To focus on times when Irukandji were present, months when stings never occurred in a region were excluded from the analysis – this is generally the winter months. For model selection, we used Akaike Information Criterion (AIC), which is an estimate of the relative quality of models given the data (Akaike 1974), to choose the most parsimonious model. We thus do not talk about significant predictors, but important ones, consistent with information theoretic approaches.

Finally, we investigated whether the sea level pressure difference between Darwin and Tahiti, as expressed by the Southern Oscillation Index (SOI), influenced the frequency of Irukandji stings seasonally or interannually. Factors were fitted for each month and each year for each of the regions. However, there was no correlation between the seasonal cycles or interannual variation of Irukandji stings and the SOI.

3.0 RESULTS

3.1 The Australian Venomous Jellyfish Database (AVJD)

3.1.1 Geographical distribution of data

The distribution of GBR Irukandji stings in the database from 1985-2016 is shown in Figure 3A at a resolution of 0.5°. There are three relatively distinct regions where most stings occur: Cairns, Townsville and Whitsundays (Figure 3B-D). Most stings were found off Cairns (n=641, 59.9%), Townsville (n=202, 18.9%), Whitsundays (n=228, 21.3%). These regions were used to subset the data in subsequent analyses using GLMs.

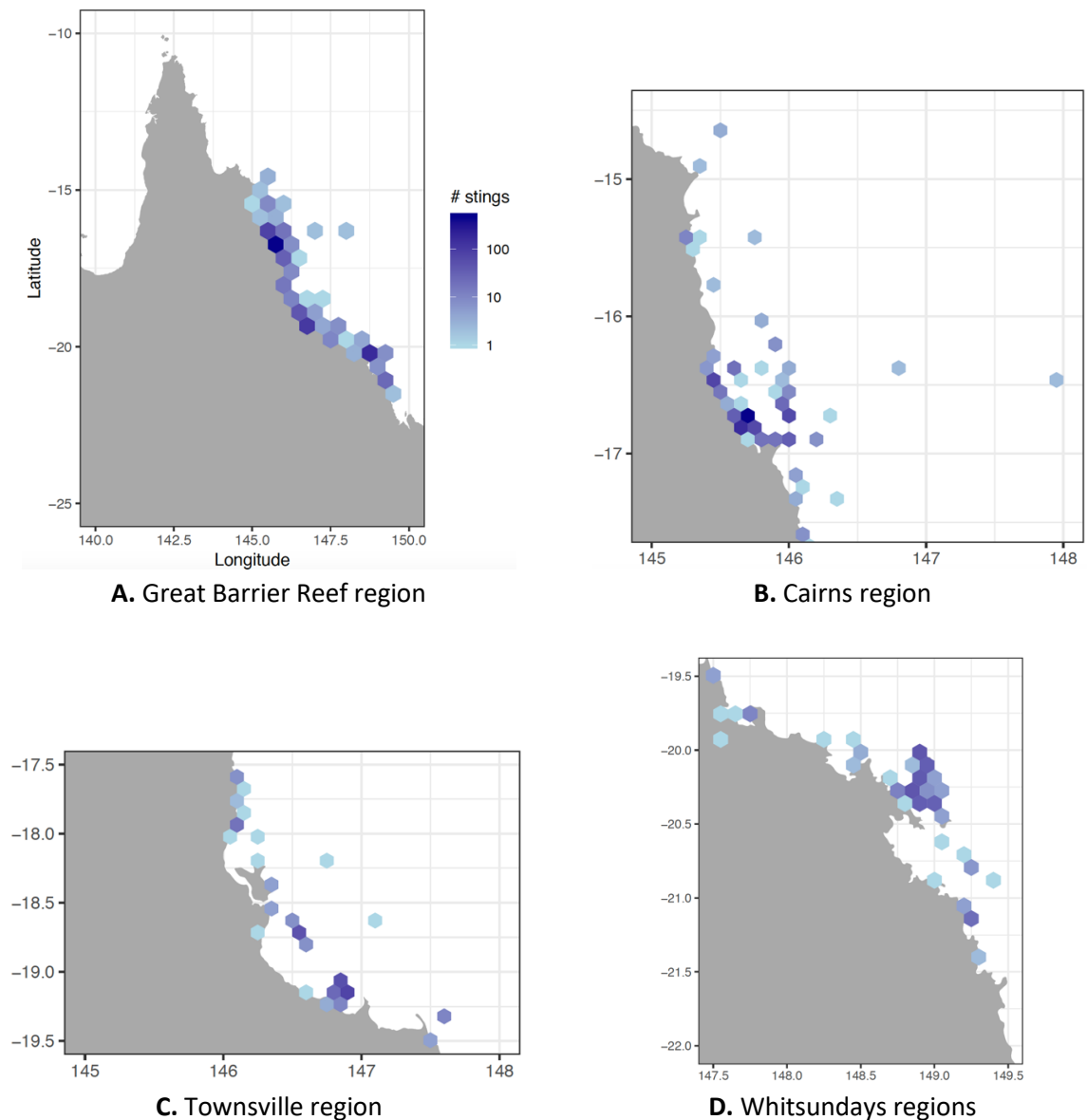
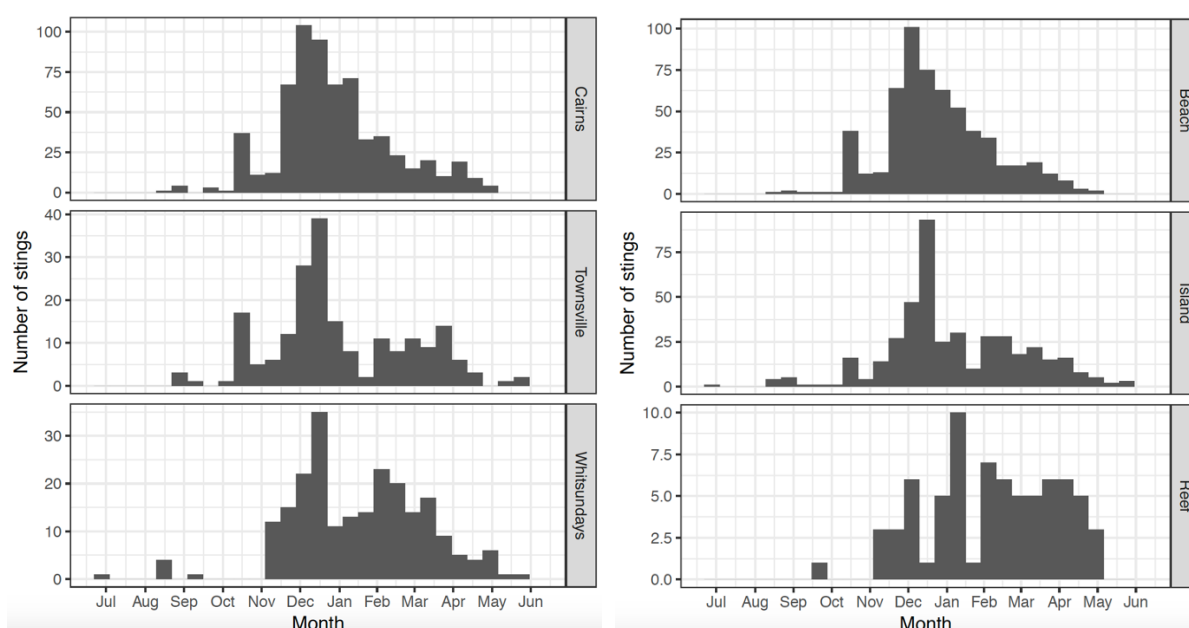


Figure 3: Locations of stings in the Irukandji database that were used in the analysis. (A) The Great Barrier Reef region, revealing three main subregions of stings. These regions are: (B) Cairns; (C) Townsville; and (D) Whitsundays. Note that a log₁₀ scale is used.

Although most stings were coastal, all three regions have stings further offshore on Islands and Reefs (Figure 3). Over the past 32-years (1985-2016) in Cairns there were 490 stings on the Beach, 90 stings on Islands, and 61 stings on the Reef. However, in the other two regions, most stings were on islands. In the Townsville region there were 38 stings on the Beach, 154 stings on Islands, and 10 stings on the Reef. In the Whitsundays there were 46 stings on the Beach, 180 stings on Islands, and 2 stings on the Reef. In Cairns, statistical analysis could be performed in all three areas (Beach, Island, Reef), whereas in Townsville and Whitsundays, Reef data were combined with data from the Islands owing to the small number of stings on Reefs.

3.1.2 Seasonal distribution of data

Most Irukandji stings occurred during summer (December–February) in all three Regions, with the majority later in the season (January–June): 58.0% in Cairns, 54.5% in Townsville and 63.2% in the Whitsundays (Figure 4A). There are marked differences in the seasonal cycles in the different Areas, with more stings later in the season as you move offshore (Figure 4B). For example, 54.5% of the stings on the Beach were between January and June, compared to 63.4% on Islands, and 82.2% on Reefs.



A. Seasonal cycle of stings by region.

B. Seasonal cycle of stings by zone.

Figure 4: Seasonal cycle of stings recorded in the AVJD shown by (A) region; and (B) zone.

3.2 Irukandji sensitivity to water quality

3.2.1 Sensitivity to pesticides

The number of polyps increased in all treatments throughout the 33 days of the experiment (Table 1 and Figure 5). Although there appeared to be large differences in the number of polyps

between some treatments, differences were not statistically significant (Table 1). Most polyps survived, however, polyp mortality was observed in 7 replicates. Mortality was only observed in pesticide treatments and no polyps died in the controls. The power analysis indicated that to correctly reject the null hypothesis at the observed effect size of the current study, at least 7 replicates would have been required in each treatment.

The mobility of polyps (Table 2 and Figure 6) and consumption of brine shrimp (Table 3 and Figure 7) did not differ among treatments.

Table 1: LMMs results for polyp asexual reproduction throughout the experiment (df = degrees of freedom).

Variable			Asexual reproduction	
Transformation			ln(x)	
Information criteria			BIC= 305.041	
			AIC= 297.479	
Source	df	denominator df	F	P
Day	8	258.34	49.65	<0.001
Atrazine	2	48.97	1.704	0.193
Imidacloprid	2	48.947	0.329	0.721
Day x Atrazine	16	258.338	0.850	0.628
Day x Imidacloprid	16	258.338	1.015	0.441
Atrazine x Imidacloprid	4		1.48	0.222
Day x Atrazine x Imidacloprid	32	258.338	0.845	0.709

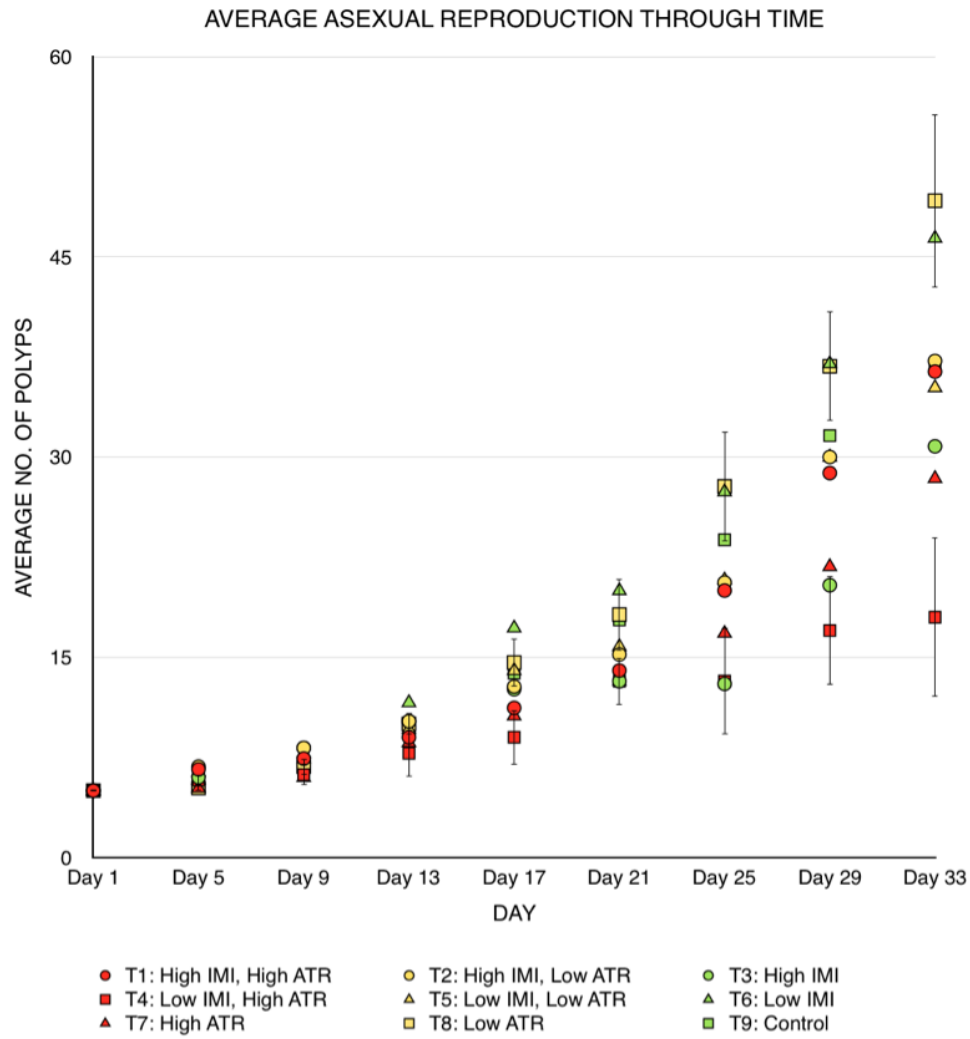


Figure 5: Number of polyps (mean +/- SE) among treatments throughout the pesticide exposure experiments.

Table 2: LMMs results for feeding ability (% brine shrimp consumed).

Variable	Feeding ability			
Transformation	$\ln(x+1)$			
Information criteria	BIC= 621.668			
	AIC= 618.526			
Source	df	denominator df	F	P
Atrazine	2	171	0.886	0.414
Imidacloprid	2	171	1.593	0.206
Atrazine x Imidacloprid	4	171	1.663	0.161

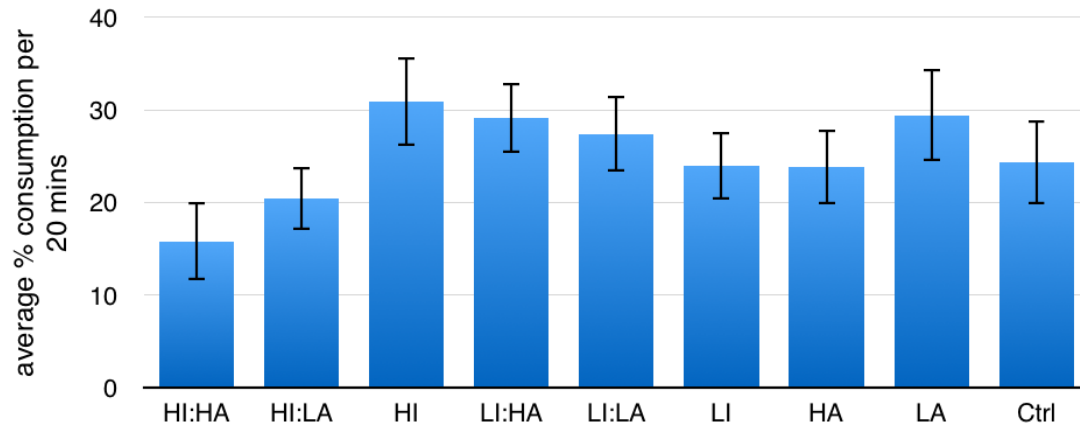


Figure 6: Mean percentage of brine shrimp consumed 20 mins⁻¹ (mean $\pm$ SE) among treatments (HI = High Imidacloprid, HA = High Atrazine, LI = Low Imidacloprid, LA = Low Atrazine, Ctrl = Control).

Table 3: LMMs with results for mean mobility (mean % pixel change per sample).

Variable			Mean mobility	
Transformation			ln(x)	
Information criteria			BIC= 89.991	
			AIC= 87.604	
Source	df	denominator df	F	P
Day	1	72	1.774	0.187
Atrazine	2	72	1.467	0.237
Imidacloprid	2	72	0.568	0.569
Day x Atrazine	2	72	0.190	0.827
Day x Imidacloprid	2	72	1.662	0.197
Atrazine x Imidacloprid	4	72	1.604	0.183
Day x Atrazine x Imidacloprid	4	72	0.586	0.674

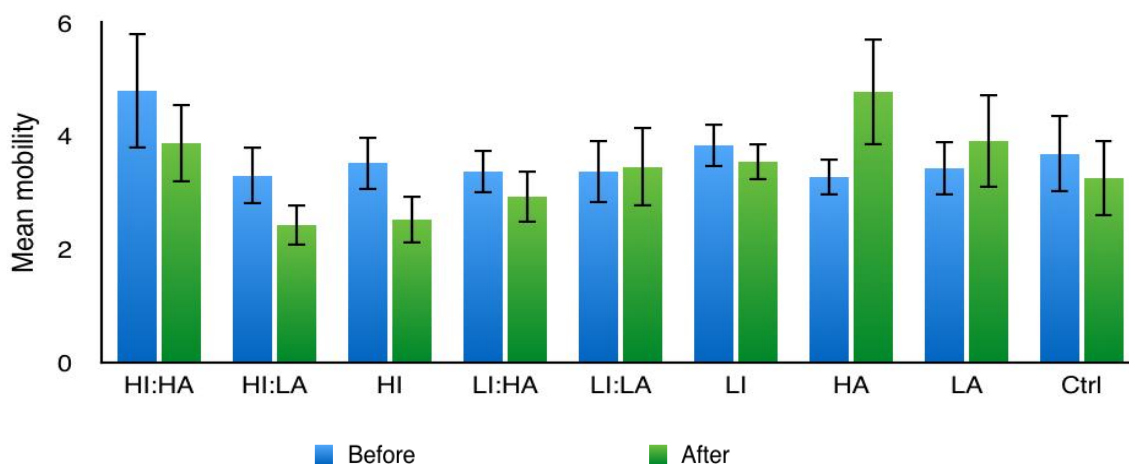


Figure 7: Mean (+/- SE) mobility (% change in pixels) among treatments at the beginning and end of the experiment. (HI = High Imidacloprid, HA = High Atrazine, LI = Low Imidacloprid, LA = Low Atrazine, Ctrl = Control).

This was the first study to examine the effects of any pesticides on a cubozoan species. Polyps displayed no response to Imidacloprid or Atrazine, regardless of whether they were exposed to the pesticides individually or concurrently. Moreover, the polyps survived exposure to the highest pesticide concentrations found in the GBR lagoon for more than a month. The benthic life stage of this cubozoan species, therefore, appears to be robust to commonly used pesticides. These observations imply that even the highest concentrations of Atrazine and Imidacloprid currently found in the GBR's inshore waters are unlikely to have a detrimental effect on *M. maxima* polyp populations.

3.2.1 Sensitivity to pCO_2 and ocean warming

There were significant individual effects of pH (pH $\times$ day) and temperature (temperature $\times$ day) on asexual reproduction throughout the experiment (Table 4 and Figure 8). Twice as many swimming polyps were produced at 25°C than at 28°C. Slightly more swimming polyps were produced at pH 8 than pH 7.9 and fewest swimming polyps were produced in pH 7.7. Respiration rates varied among pH treatments, but patterns differed slightly depending on temperature (pH $\times$ temperature $\times$ day interaction; Table 5). In both temperature treatments, respiration rates greatly increased in the pH 7.7 treatment before decreasing towards the end of the experiment, but respiration rates increased more at pH 7.7 in the warmer treatment (Figure 9).

Mobility of polyps was greater at the end of the experiment in the pH 8 and pH 7.7 treatments regardless of temperature (Table 6). In the pH 7.7 treatment, mobility was reduced after the experiment in the 28°C but unchanged at 25°C (Figure 10).

Table 4: Summary of results of a linear mixed-models analysis of the number of swimming polyps (n = 48) produced in each day (days 2, 5, 8 and 11) between treatments in the experiment.

Source	Numerator df	Denominator df	F	P
pH	2	35.58	15.61	0.182
Temperature	1	71.73	16.41	0.104
Day	1	98.22	1.40	0.169
pH × temperature	2	35.58	0.697	0.980
pH × day	2	32.56	3.60	<0.001
Temperature × day	1	98.22	17.36	<0.001
pH × temperature × day	2	32.56	0.109	0.897

The model of best fit is AR (1) Heterogeneous: -2 Restricted Log Likelihood = 61.636, Akaike's Information Criterion (AIC) = 117.636

df = degrees of freedom

P values in bold are statistically significant ($P < 0.05$). Data were $\ln(x+1)$ transformed.

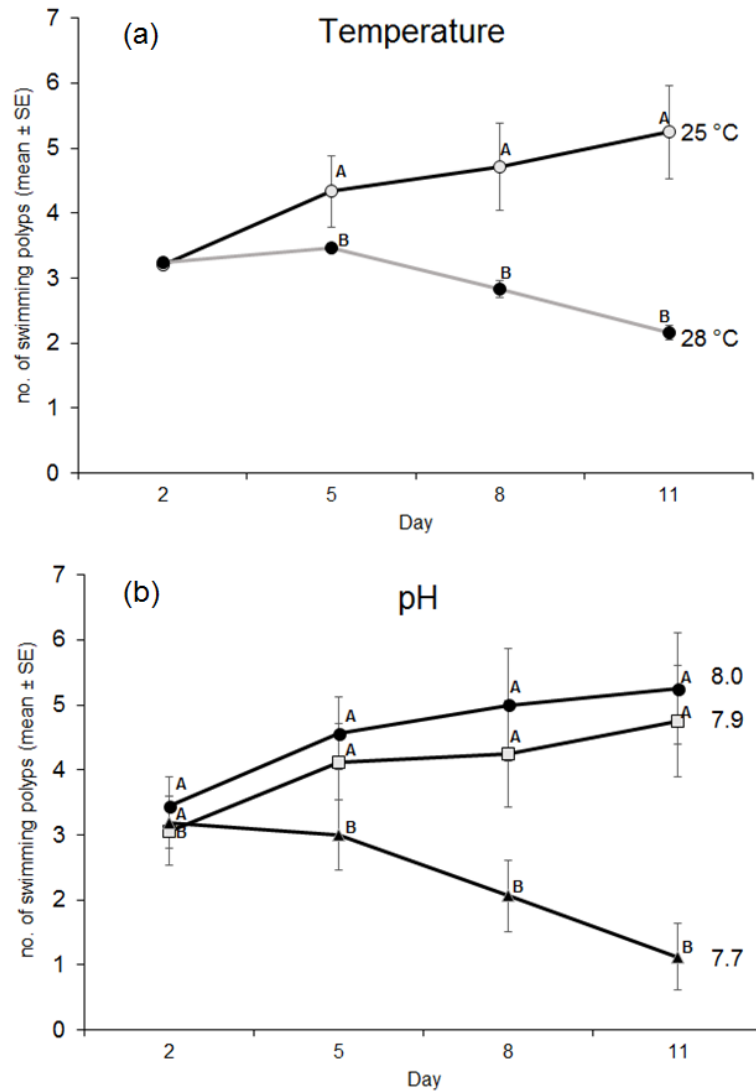


Figure 8: Number of swimming polyps (mean ± SE) recorded per day in the experiment. Letters above data points indicate similarities (e.g. AA) and differences (e.g. AB) between temperature (a) and pH (b) treatments within each day based on estimated marginal means.

Table 5: Summary of results of a linear mixed-models analysis of the respiration rates of polyps in each day (days 0, 1, 4, 7, 8, 10 and 13) between treatments in the experiment.

The model of best fit is Diagonal: 2 Restricted Log Likelihood = -241.319,

Source	Numerator df	Denominator df	F	P
pH	2	64.964	73.383	< 0.001
Temperature	1	64.964	13.052	< 0.001
Day	6	26.304	34.861	0.001
pH × temperature	2	64.964	4.958	< 0.001
pH × day	12	26.304	28.115	< 0.001
Temperature × day	6	26.304	5.980	< 0.001
pH × temperature × day	12	26.304	1.738	0.115

Akaike's Information Criterion (AIC) = -227.319

df = degrees of freedom

P values in bold are statistically significant ($P < 0.05$). Data were ln transformed.

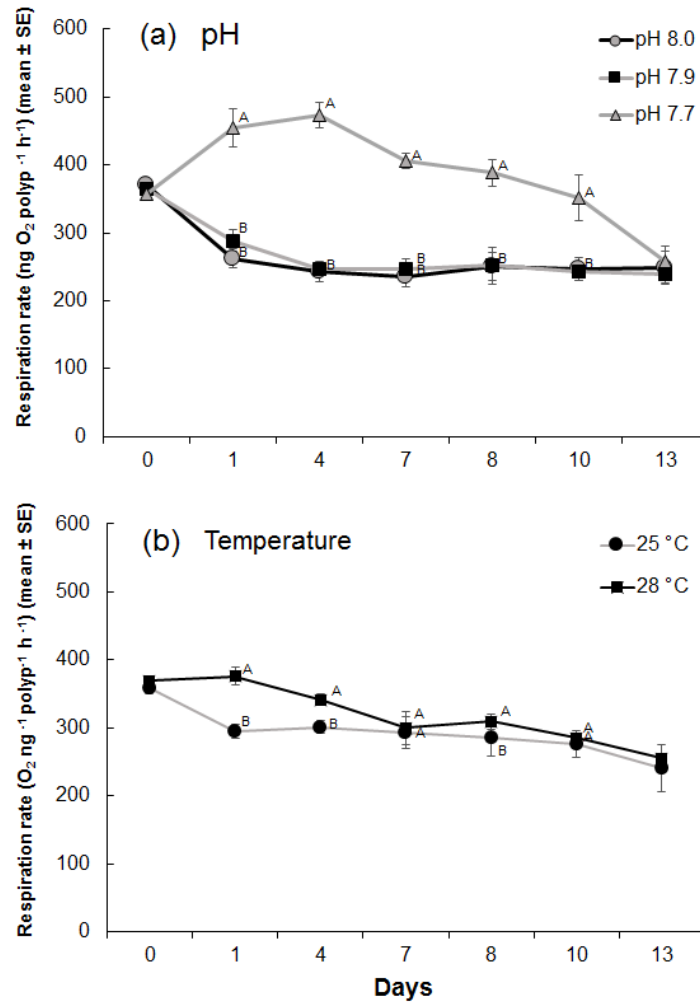


Figure 9: Respiration rates of polyps (mean ± SE) in the pH (8.0, 7.9, 7.7) (a) and temperature treatments (25 °C, 28 °C) (b) throughout the experiment. Letters above data points indicate similarities (e.g. AA) and differences (e.g. AB) between temperature and pH treatments within each day based on estimated marginal means.

Table 6: Summary of results of a linear mixed-models analysis of the mobility of polyps before and after exposure to pH and temperature treatments in the experiment.

Source	Numerator df	Denominator df	F	P
pH	2	40.571	38.88	< 0.001
Temperature	1	40.571	0.036	0.851
Before v. after	1	40.571	18.61	< 0.001
pH × temperature	2	40.571	4.79	0.014
pH × before v. after	2	40.571	27.72	< 0.001
Temperature × before v. after	1	40.571	2.67	0.110
pH × temperature × before v. after	2	40.571	2.26	0.117

The model of best fit is Diagonal: -2 Restricted Log Likelihood = -36.638,

Akaike's Information Criterion (AIC) = -32.638

df = degrees of freedom

P values in bold are statistically significant ($P < 0.05$). Data were ln transformed.

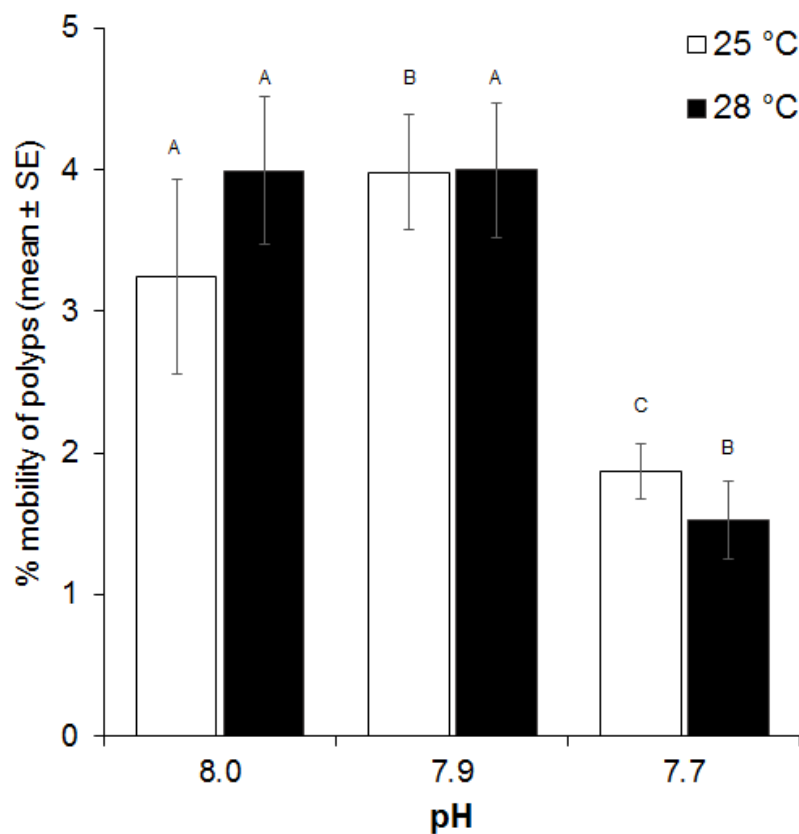


Figure 10: Percent (%) mobility of polyps (mean ± SE) in different levels of pH in ambient (25 °C) (white bars) and elevated (28 °C) (black bars) temperature scenarios. Averages were calculated from % mobility before and after exposure to experimental treatments. Letters above error bars indicate similarities (e.g. AA) and differences (e.g. AB) between pH treatments in each temperature condition based on estimated marginal means.

All polyps survived the experiment indicating that *Carukia barnesi* can tolerate even the most extreme climate conditions predicted for end-of-century. We detected multiple sub-lethal effects, however, that may reduce overall fitness and, therefore, the risk posed by *C. barnesi* in the future. Production of swimming polyps was greatly reduced under the most severe pH conditions, and only slightly reduced in the intermediate pH treatment (7.9), which is the most likely scenario for end-of-century. Productivity was also substantially reduced under elevated temperatures but, interestingly, no interaction between temperature and pH was found, indicating that exposure to the dual stressors was no worse than exposure to individual stressors. Hence, warming and reduced pH may reduce production of *C. barnesi* populations in the future. The stress caused by exposure to elevated temperature and reduced pH also manifest as increased respiration rates. In this case, exposure to the dual stressors caused greater respiratory distress than exposure to individual stressors. At the end of the experiment, motility of polyps was greatly reduced in the most extreme pH treatment, which may impair a polyp's ability to capture prey in the future. Hence, although *C. barnesi* can tolerate changing ocean conditions, it is likely that overall fitness and, therefore, productivity of populations may be reduced, which would lessen the risk posed by *C. barnesi* to the public.

3.3 Improved techniques for detection and identification of Irukandji

Multiple cubozoans and scyphozoans were detected using JellyCams, including Irukandji, stingers (*Chironex fleckeri*) (Figure 11) and harmless scyphozoans (Figure 12). At Yorkeys Knob, a total of 148 jellyfish were recorded over the 2016-17 and 2017-18 seasons, consisting of 85% cubozoans and 15% scyphozoans. This included the Irukandji species *Morbakka fenneri* (4%) and unidentified cubozoans (63%). The cubozoan *C. fleckeri* made up 19% of those jellyfishes (5% adult and 14% juvenile). The remaining species were of Class Scyphozoa as follows; *Netrostoma nuda* (7%), *Phyllorhiza* sp. (4%) and other unidentified scyphozoans (2%) and unidentified jellyfish (1%).

There were strongly contrasting patterns of abundance of cubozoans between the two seasons. Multiple cubozoans were observed in 2016-17, all between late February and early May with no obvious change in local wind patterns (Figure 13). These observations also corresponded to the highest ever water temperatures (33.3°C) at which cubozoans have been found (Table 7). In contrast, only three individuals were recorded in 2017-18, all in March. Abundances in both seasons were consistent with what SLSQ detected on the beaches over the same time periods.

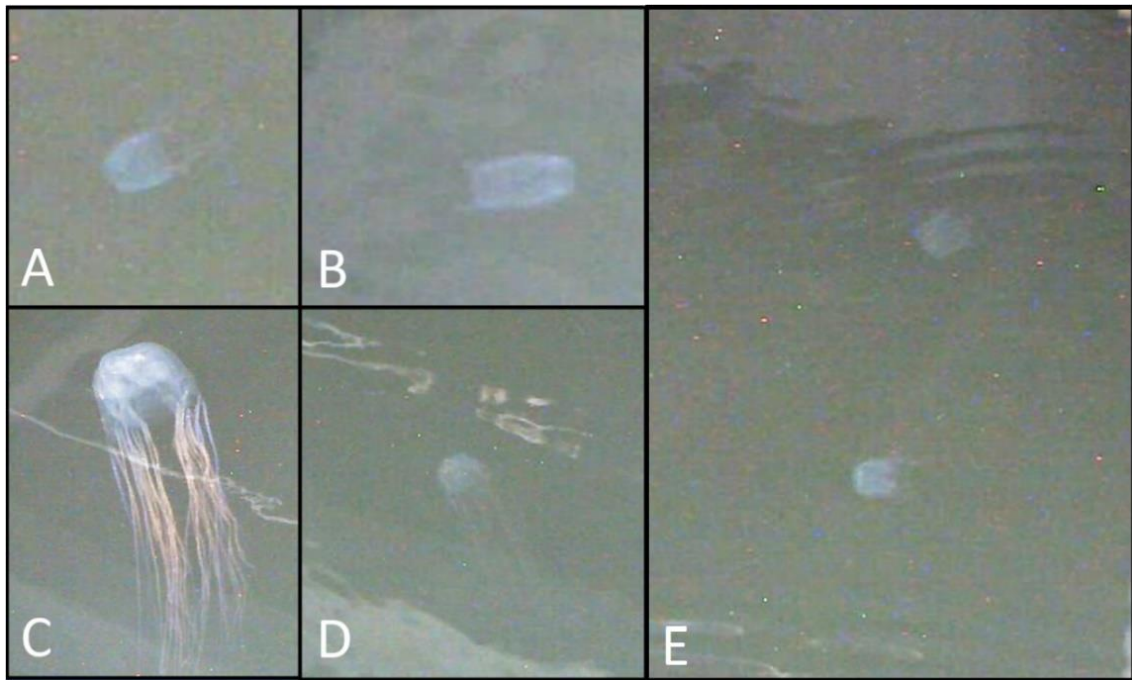


Figure 11: Examples of cubozoans detected by JellyCams. (A) An unidentified cubozoan that may be the Irukandji *Gerorgia rifkinae*, a juvenile box jellyfish *Chironex fleckeri*, or “the other box jellyfish” *Chiropsella bronzie* -- distinct cuboid shape, relatively small, blue tinge, indistinct number of tentacles extending from each pedalium. (B) *Morbakka fenneri* – elongated cuboid shape, small, blue tinge, single tentacle. (C) *Chironex fleckeri* (adult) – cuboid shape, relatively large (>15cm bell diameter), blue bell with brownish tentacles, multiple flat tentacles. (D) *Chironex fleckeri* (juvenile) – cuboid shape, relatively small (<15cm bell diameter), multiple tentacles. (E) Unidentified cubozoans similar to (A) – similar shape, size and colouring, but upper animal orientated to hide evidence of tentacles.

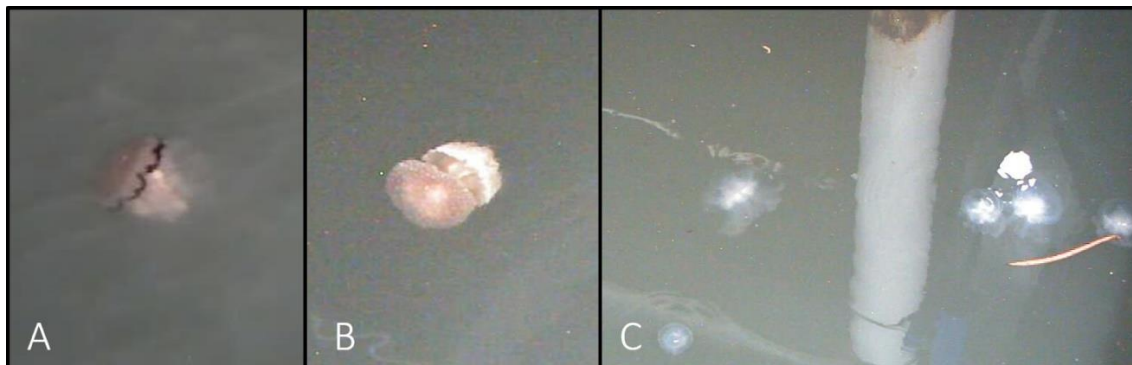


Figure 12: Examples of scyphozoans detected by JellyCams. (A) *Cyanea barkeri* (Lion’s mane) – distinct dark line around bell, numerous tentacles which are ‘hair-like’ giving the common nickname ‘hair jelly’. (B) *Phyllorhiza* sp. – barrel-shaped with white spots and stumpy oral arms. (C) *Netrostoma nuda* – ‘door-knob’ shaped giving their common nickname, white-clear colour, stumpy tentacles.

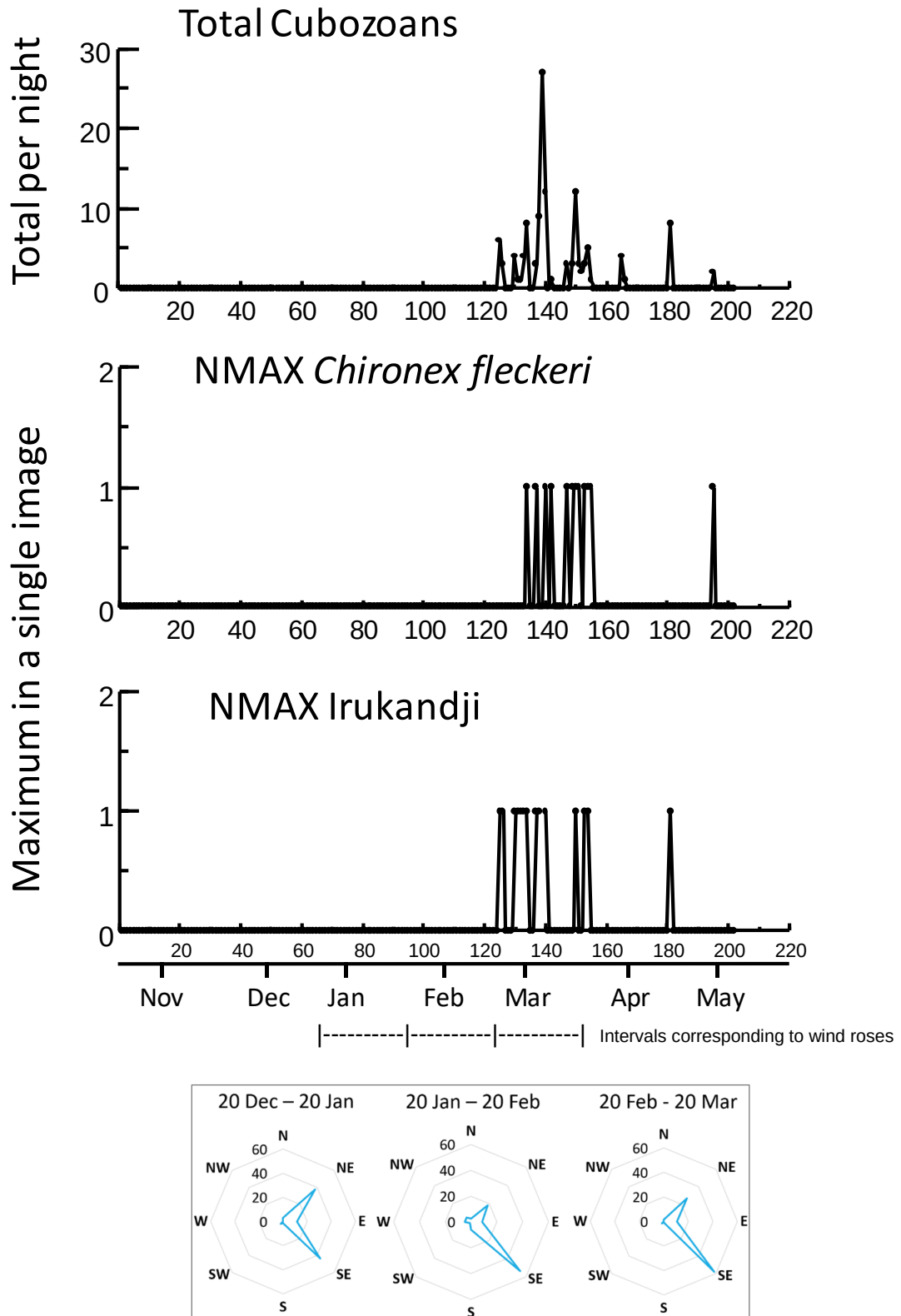


Figure 13: Abundance of cubozoans in 2016-17 at Yorkeys Knob, near Cairns. Data are presented for total cubozoans observed per night (top) and as the maximum number of stingers (*Chironex fleckeri*) (centre) and Irukandji (bottom) observed in any single image during the night. The x-axis shows both month and the number of days from when sampling commenced. There are no obvious differences between monthly wind statistics (Cairns SLSA sites) from periods when cubozoans were absent (20 Dec–20 Feb) and when they were present (20 Feb–20 Mar), confirming the need to consider daily variability across multiple seasons.

Table 7: Comparison of minimum and maximum temperatures recorded at each site (orange) and the range in which cubozoans (blue) were seen in both Cairns and previous findings of Llewellyn et al (2016).

Temperature	Cairns			Llewellyn et al (2016)	
	Site	<i>C. fleckeri</i>	Irukandji sp.	<i>C. fleckeri</i>	Irukandji sp.
Minimum	26.3°C	26.6°C	26.6°C	21.7°C	20.2°C
Maximum	33.8°C	33.3°C	33.3°C	31.6°C	30.2°C

On the Strand in Townsville, no cubozoans were detected using JellyCams in either 2016-17 or 2017-18, compared to multiple sightings in most prior years (Kingsford et al 2012). This absence concurred with SLSQ records for the area, with only one *Chironex fleckeri* and no Irukandji recorded at the nearby Townsville marina and none at the Strand. Despite large variations in winds and rainfall in the seasons we studied (Figure 14), *C. fleckeri* did not appear. These findings suggest local recruitment failure in recent years.

The extensive array of IrukandjiCams around the eastern and southern sides of Magnetic Island detected Irukandji along the northern half of the east coast, but none around the southern coastline (Figure 1c). Very clear local differences in abundance were found on a scale of kilometres, providing further evidenced that these species tend to have very localised distributions.

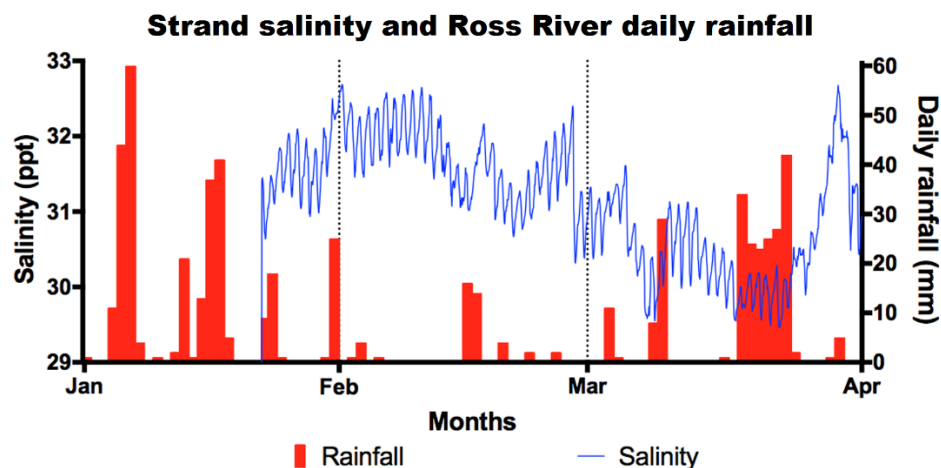


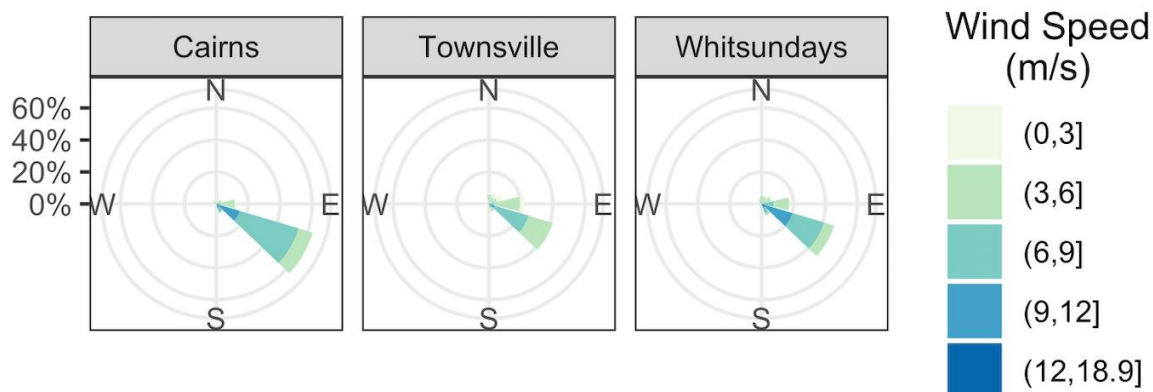
Figure 14: Daily rainfall (red) from the nearest freshwater output to the Strand (Bohle River station on the Ross River) and data from a logger that measured salinity (blue) from January–April 2017.

3.4 Relationships between Irukandji stings and environmental conditions

3.4.1 Wind conditions

Looking at the GBR overall, south-easterly trade winds dominate, particularly off Cairns (Figure 15a). They also dominate in all months, but less so in summer when the wind is more variable in direction (Figure 15b). Summer is the time that Irukandji sting events most often occur.

(a)



(b)

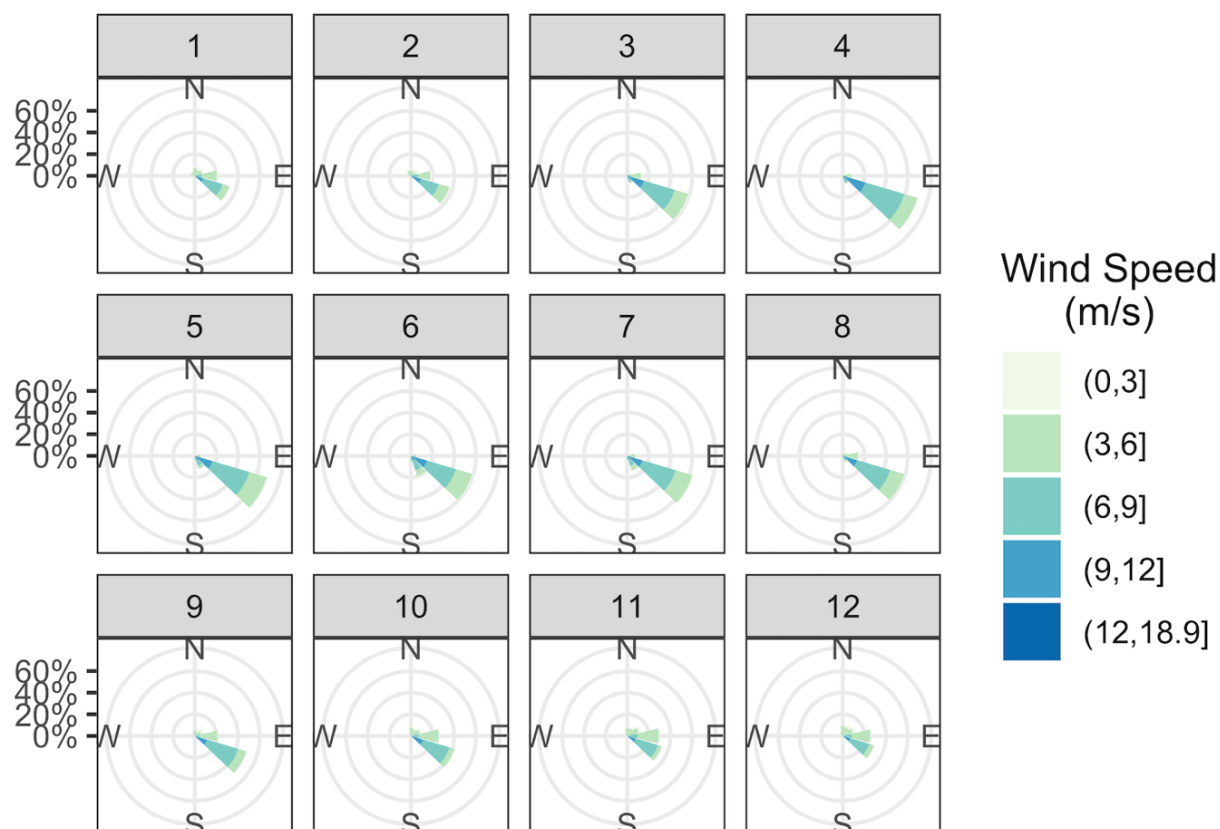


Figure 15: Frequency, speed and direction of wind (a) in the three regions; and (b) over the 12 months of the year (numbered 1-12) for the whole GBR region.

3.4.2 Cairns Beaches

The wind on Cairns Beaches on the days when there were no stings, 1 sting, 2 stings and >2 stings is shown in Figure 16. When there were no stings, south-easterly wind dominated. As the number of stings per day increased, there was a greater proportion of westerly, north-westerly, and south-westerly winds. Winds were also weaker when there were more stings. Note that there are still south-easterly winds when there are sting events, but they are far less frequent.

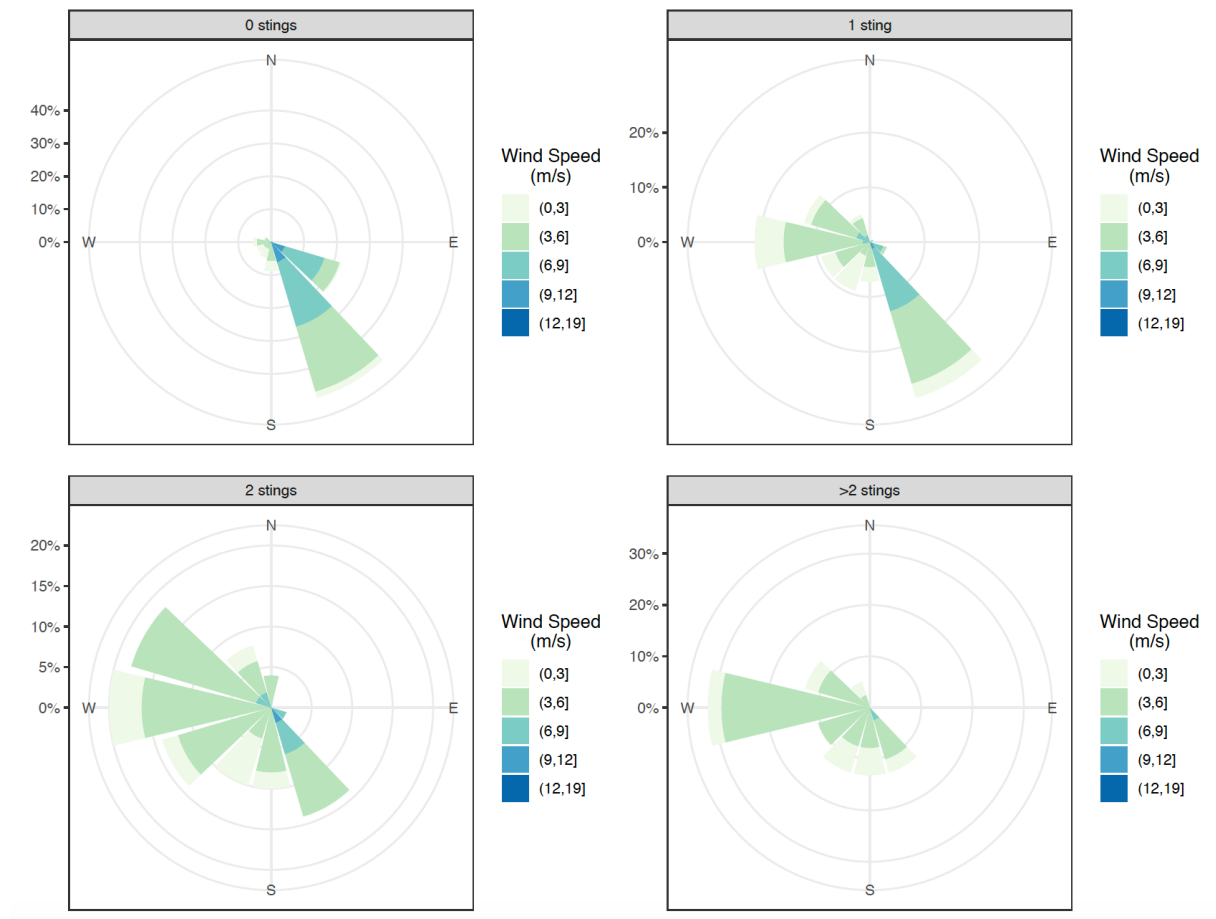


Figure 16: Winds for Cairns beaches on days with increasing numbers of stings.

The generalised linear model for the number of Irukandji stings per day on Cairns beaches explained 28.5% of the variance (Figure 17). Stings were highest from November to April. There were fewer stings when winds were from the south-easterly direction than other directions, with most stings during north-westerly winds followed by north-easterly and south-westerly winds. There were also more stings when winds were weaker ($< 5 \text{ m s}^{-1}$). Of the 1-15 days before the sting that were investigated, strongest relationships were for winds over the 3-days previous to the sting event. This was generally true for all regions; predictability increased when winds were averaged from 1 to 3 days, and then declined slowly up until 2 weeks. There was an interaction between tidal direction and height, with more stings when the tide was lower and when it was incoming.

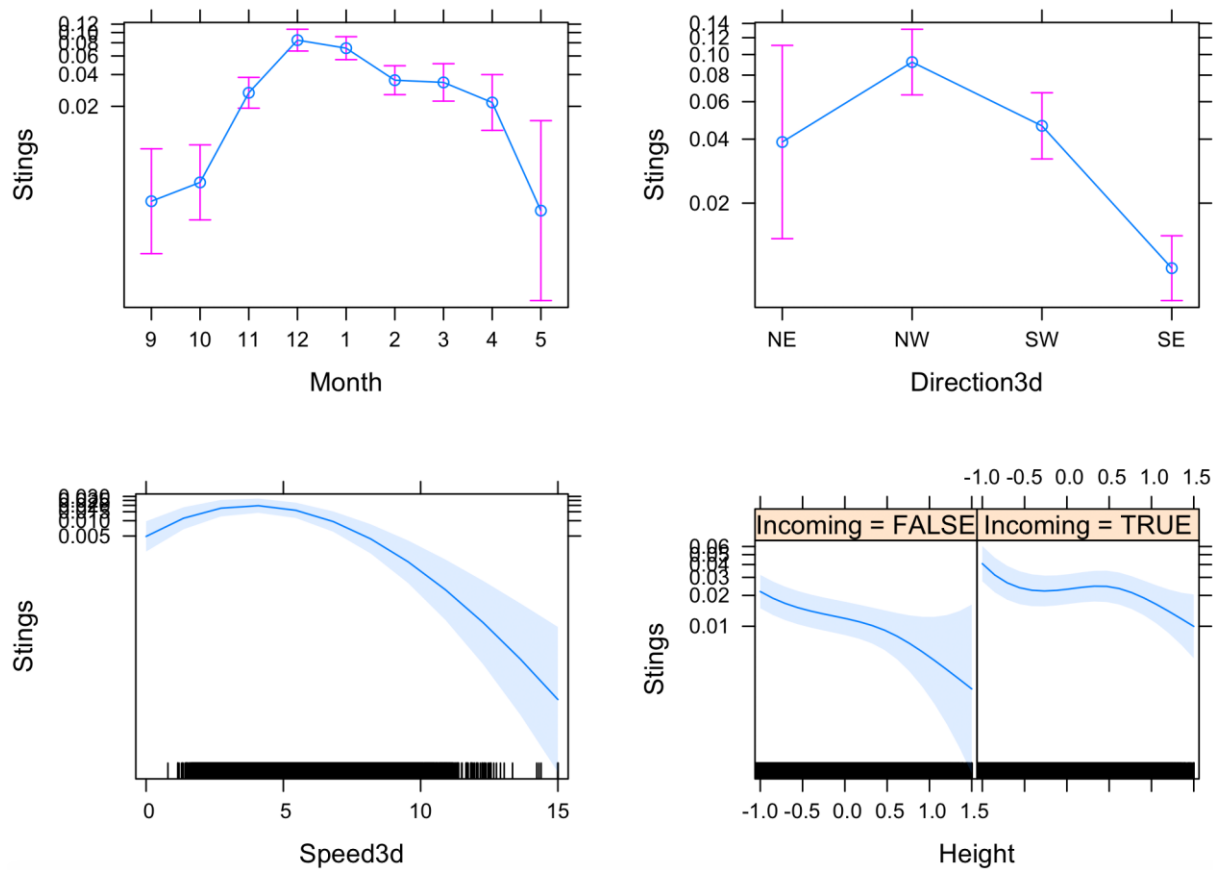


Figure 17: The final GLM of Irukandji stings for Cairns beaches.

3.4.3 Cairns Islands

The winds near Cairns Islands on days when there were no stings and when there were stings is shown in Figure 18. There were more westerly and south-westerly winds when there were Irukandji stings. Winds were substantially weaker when there were stings.

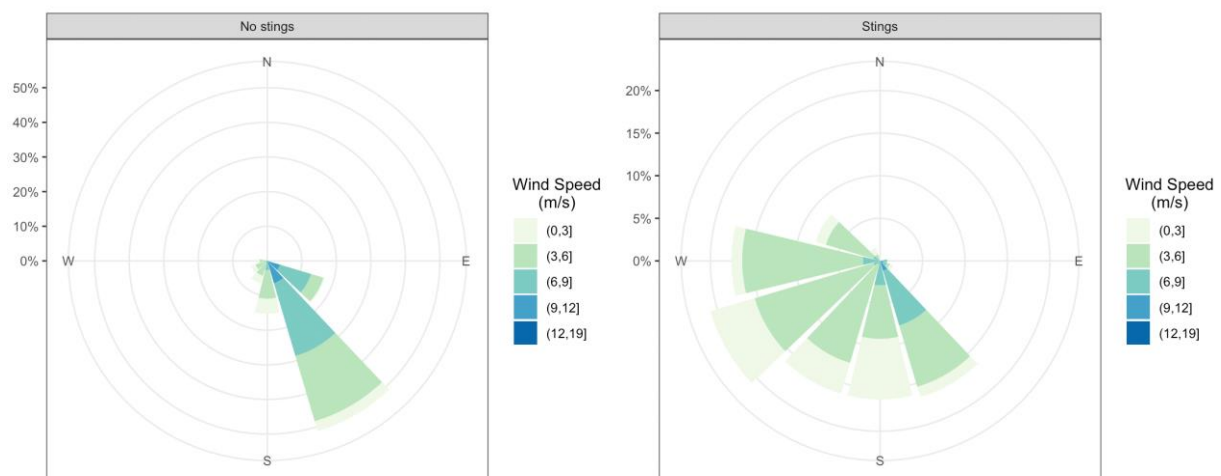


Figure 18: Winds for Cairns Islands corresponding to no stings (left) and stings (right).

The generalised linear model for the presence of Irukandji stings on Cairns Islands explained 15.3% of the variance (Figure 19). Stings were highest from December to May, extending later in the season than on Cairns beaches. Wind direction was not retained in the model, probably because wind speed was more important. The presence of stings was negatively related to wind speed for the last 3 days, with the highest likelihood of stings at low wind speeds. Tidal range was important, with more stings when there is a smaller tidal range. The interaction between incoming tide and tidal height was important, with generally more stings at lower tidal height.

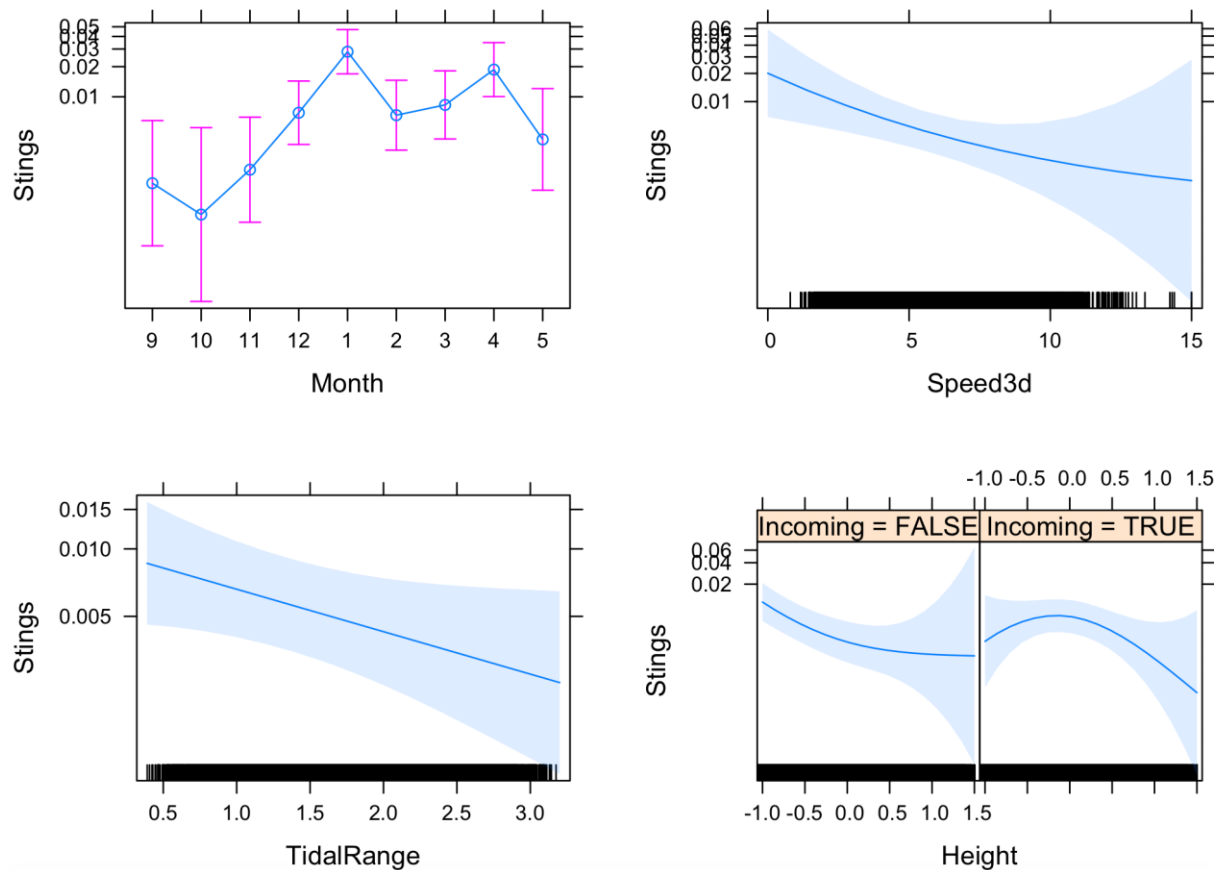


Figure 19: The final GLM of Irukandji stings for Cairns Islands.

3.4.4 Cairns Reefs

The wind on Cairns Reefs on days when there were no stings and when there were stings is shown in Figure 20. When there were sting events, there was little difference in the winds, although there might be slightly more northerly winds and a slightly greater proportion of low wind speeds.

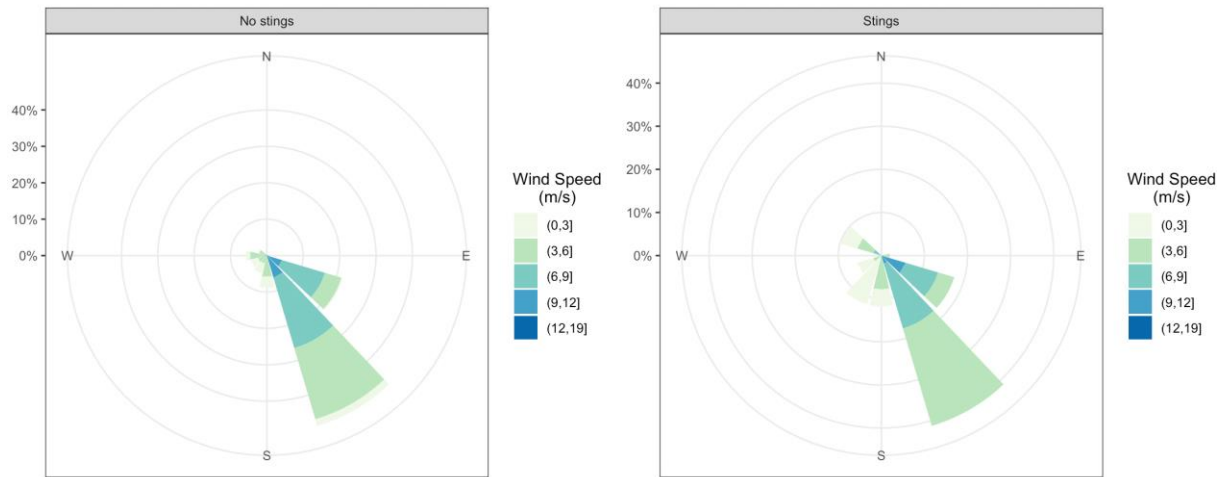


Figure 20: Winds for Cairns Reefs corresponding to no stings (left) and stings (right).

The generalised linear model for the presence of Irukandji stings on Cairns Reefs explained 6.0% of the variance (Figure 21). Stings were highest from January to May, extending later in the season than on Cairns beaches. Wind direction was not retained, but wind speed was important, with more stings at lower wind speeds. Tidal range was important, with more stings when there was a greater tidal range. The interaction between incoming tide and tidal height was not important, but the main effects were, with more stings on an incoming tide and more stings when the tidal height was low.

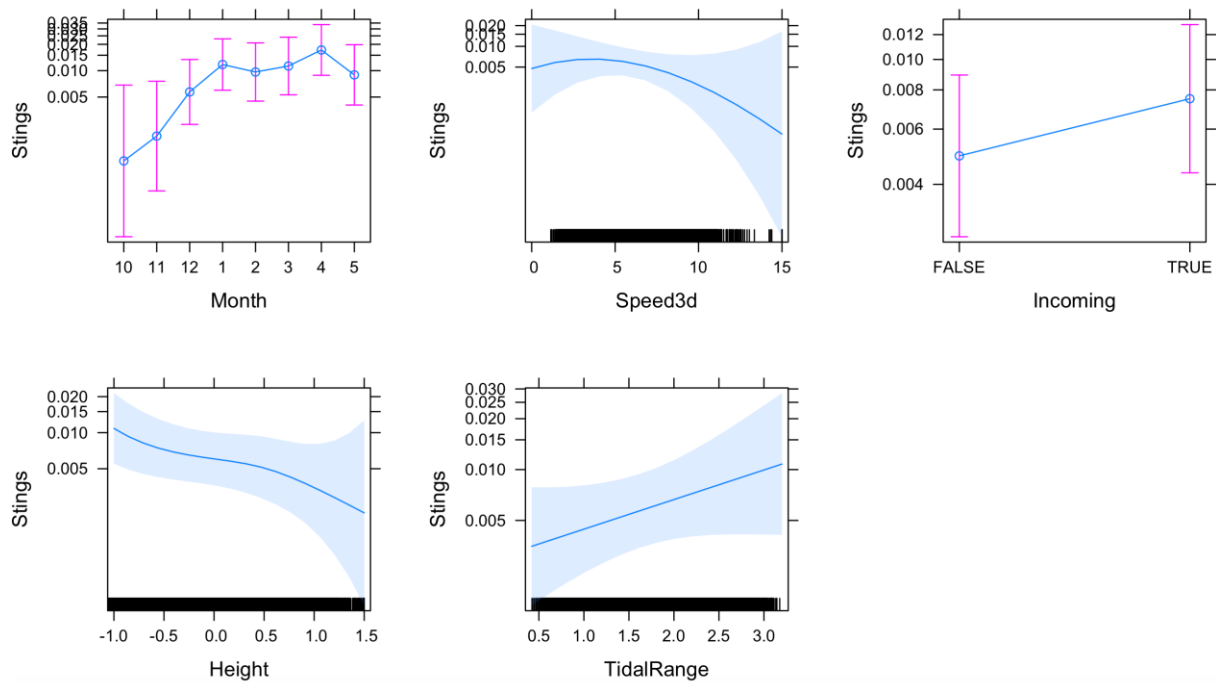


Figure 21: The final GLM of Irukandji stings for Cairns Reefs.

3.4.5 Townsville Beaches

The wind on Townsville Beaches on the days when there were no stings and stings is shown in Figure 22. When there were no stings south-easterly winds dominated, whereas sting events were accompanied by a greater proportion of westerly and south-westerly winds. There was also a greater proportion of weaker winds when there were sting events. There are still south-easterly winds when there are sting events, but they are less frequent than when there are no stings.

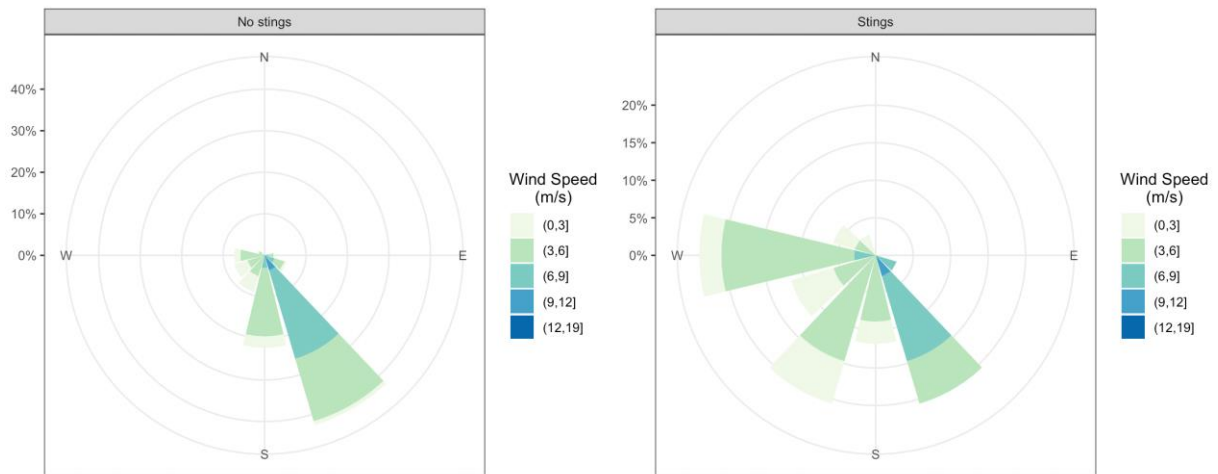


Figure 22: Winds for Townsville Beaches corresponding to no stings (left) and stings (right).

The generalised linear model for the presence of Irukandji stings on Townsville Beaches explained 7.0% of the variance (Figure 23). There was some seasonality, with more stings from November to April than in September. Wind speed was an important predictor of stings, with more stings at lower wind speeds. There were more stings during north-westerly and south-westerly winds, with fewer stings during south-easterly winds. Note that westerly winds are included as north-westerly winds in this analysis. The interaction between incoming tide and tidal height was not retained, nor was tidal height, but there was a greater likelihood of stings on an incoming tide. There were more stings where there was a greater tidal range.

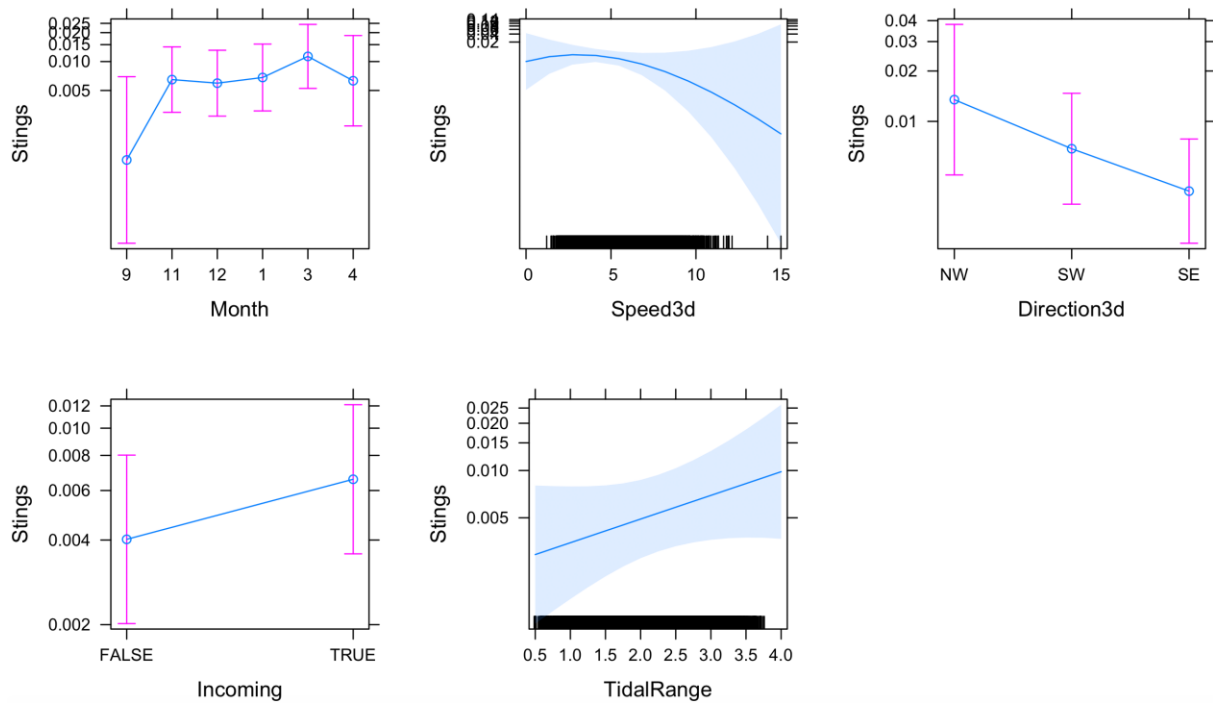


Figure 23: The final GLM of Irukandji stings for Townsville Beaches.

3.4.6 Townsville Islands and Reefs

The wind on Townsville Islands and Reefs on the days when there were no stings and stings is shown in Figure 24. When there were no stings, south-easterly winds dominated. When there were sting events, there was a greater proportion of westerly, southerly and south-westerly winds. There was also a greater proportion of weaker winds when there were sting events. There are still south-easterly winds when there are sting events.

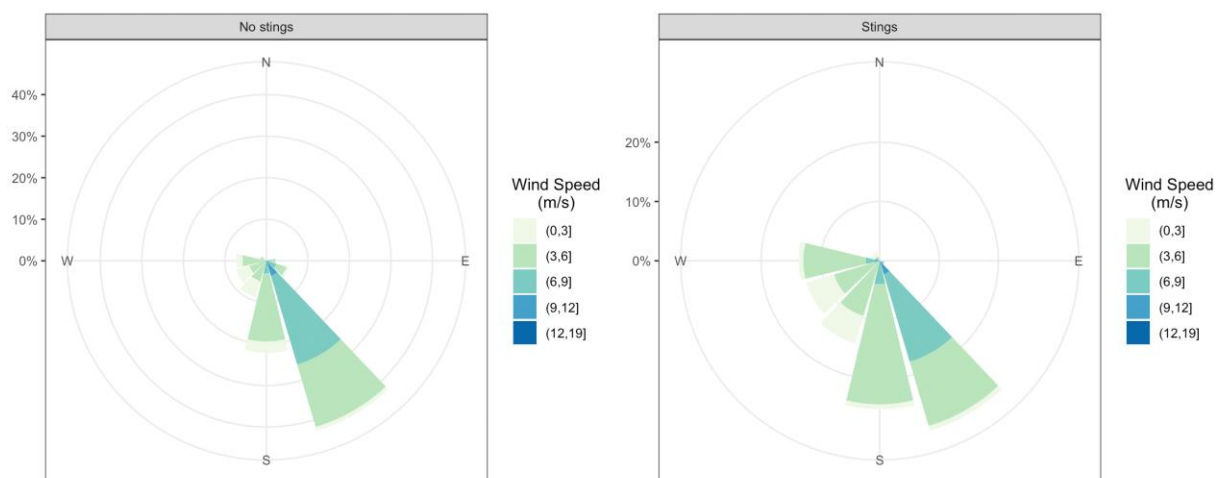


Figure 24: Winds for Townsville Islands and Reefs corresponding to no stings (left) and stings (right).

The generalised linear model for the presence of Irukandji stings on Townsville Islands and Reefs explained 9.8% of the variance (Figure 25). Stings were most common in December and remained high until April. Wind speed was not retained in the model, but wind direction was important, with a greater likelihood of stings during north-westerly winds, with fewer stings during south-easterly winds. Note that westerly winds are included as north-westerly winds in this analysis. The interaction between incoming tide and tidal height was important, with generally a greater likelihood of stings when the tidal height was low. Tidal range was retained in the model, with more stings when the tidal range is lower.

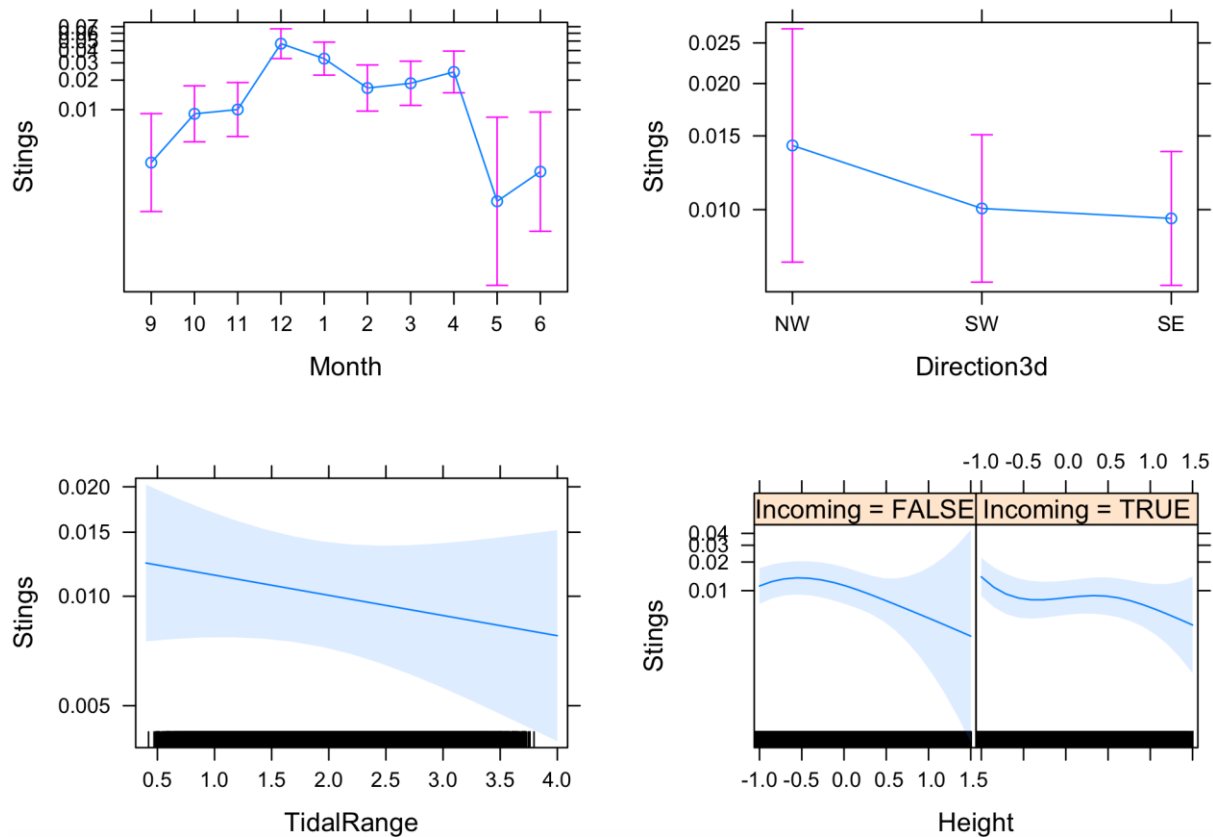


Figure 25: The final GLM of Irukandji stings for Townsville Islands and Reefs.

3.4.7 Whitsundays Beaches

The wind on Whitsundays Beaches on the days when there were no stings and stings is shown in Figure 26. South-easterly winds dominated all the time and there was relatively little difference in wind speed and direction, although there was slightly more north-westerly winds when there were stings.

The generalised linear model for the presence of Irukandji stings on Whitsundays Beaches explained 7.7% of the variance (Figure 27). There is a relatively short sting season from January to April. Wind speed was not retained in the model, but wind direction was important, with greater likelihood of stings during north-westerly winds and fewer stings during south-westerly and south-easterly winds. Tide did not influence the likelihood of stings.

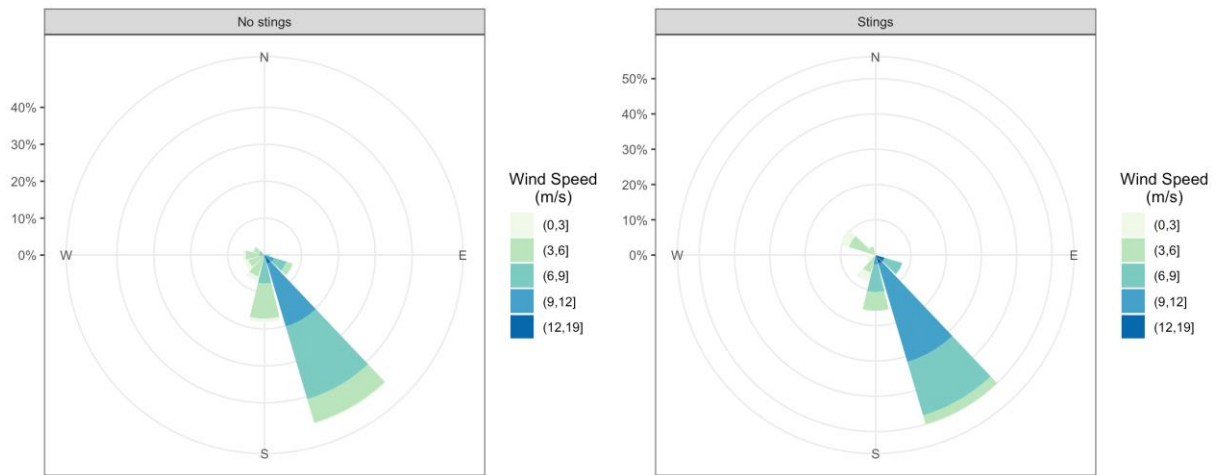


Figure 26: Winds for Whitsundays Beaches corresponding to no stings (left) and stings (right).

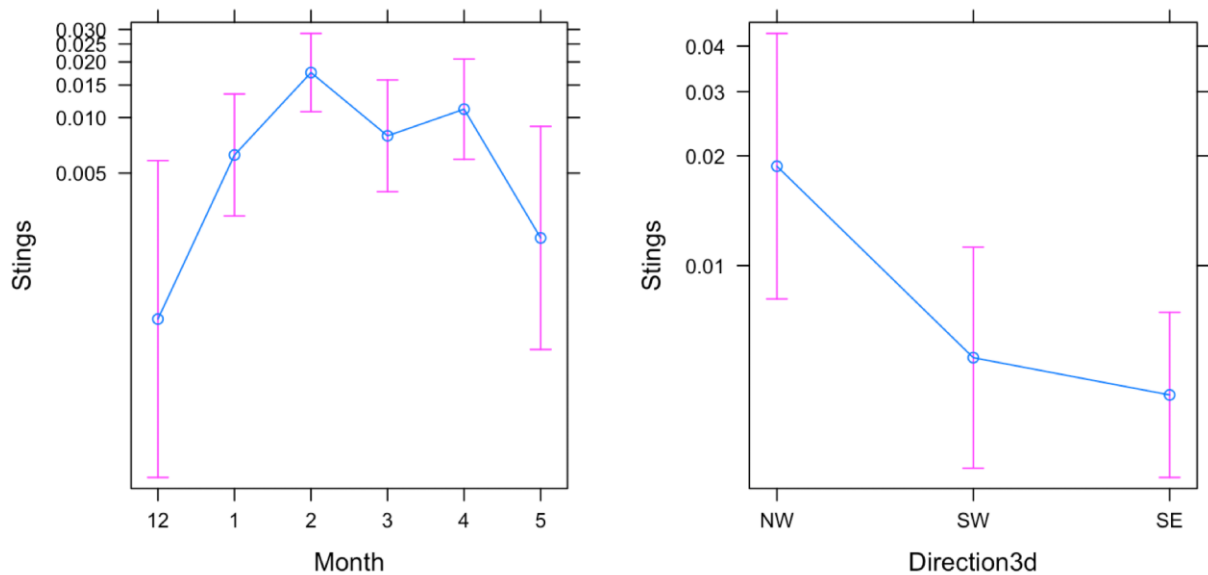


Figure 27: The final GLM of Irukandji stings for Whitsundays Beaches.

3.4.8 Whitsundays Islands and Reefs

The wind on Whitsundays Islands and Reefs on the days when there were no stings and stings is shown in Figure 28. When there were no stings, south-easterly wind dominated. When there were sting events, there was a greater proportion of south-westerly winds, but little difference in wind strength. South-easterly winds are common all the time in the area.

The generalised linear model for the presence of Irukandji stings on Whitsundays Islands and Reefs explained 13.2% of the variance (Figure 29). The likelihood of being stung is high from December to March and is lower in other months. Wind speed was not retained in the model, but wind direction was important, with greater likelihood of stings during south-westerly winds

and fewer stings during north-westerly and south-easterly winds. Tide influenced the likelihood of stings, with a higher chance of stings when the tide was low and with an incoming tide.

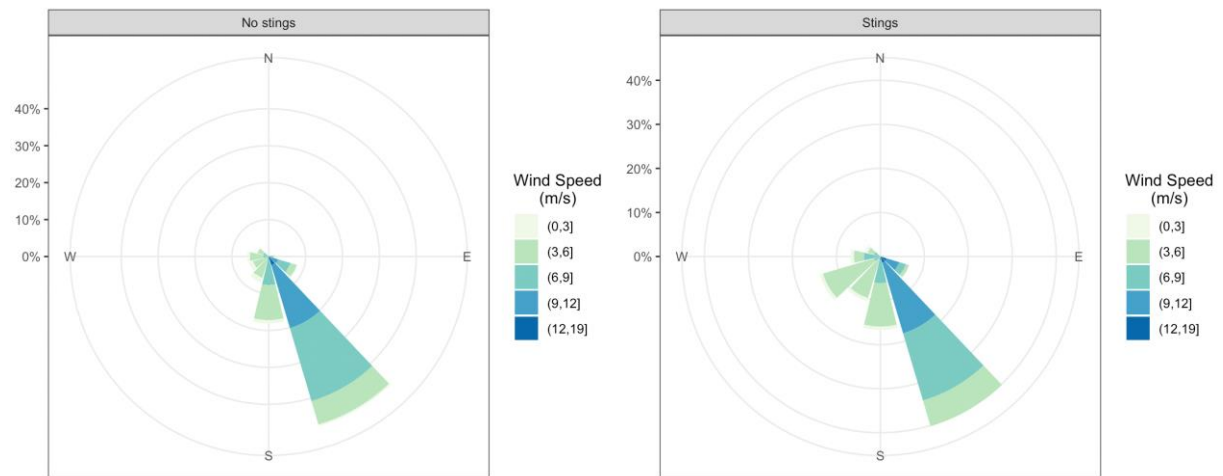


Figure 28: Winds for Whitsundays Islands and Reefs corresponding to no stings (left) and stings (right).

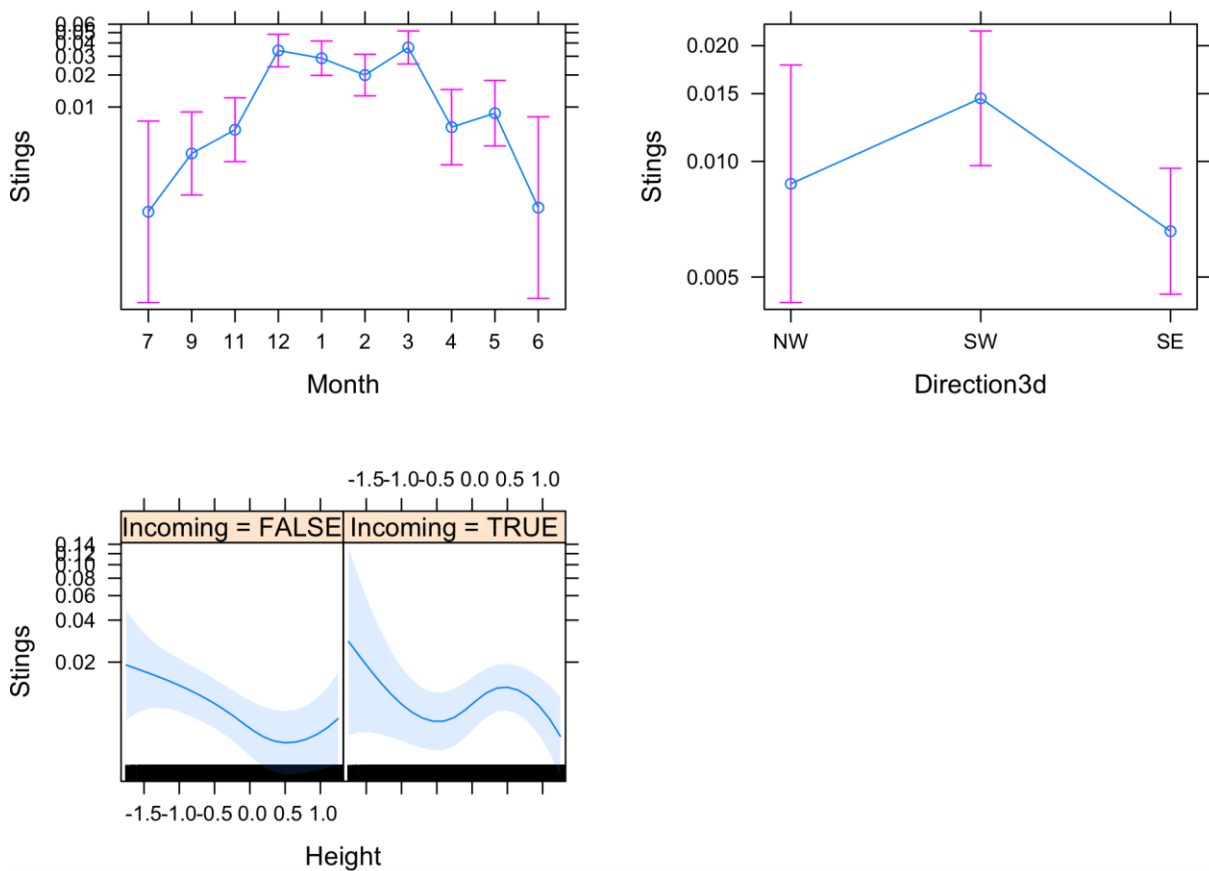


Figure 29: The final GLM of Irukandji stings for Whitsundays Islands and Reefs.

4.0 DISCUSSION

Through this project, all the key elements are now in place to implement an operational Irukandji forecasting system for the GBR that will continue to improve into the future.

First, an Australian Venomous Jellyfish Database (AVJD) has been established to capture information on the distribution of dangerous jellyfish around Australia. Its continued development is essential for ongoing evaluation and improvement of a forecasting system.

Second, methods for routinely monitoring and identifying Irukandji have been refined through development and evaluation of low-cost camera systems and viewing chambers. The technical capabilities of these devices have been successfully demonstrated, although further work is required to secure broader adoption beyond the research community.

Third, the project has supported experimental work to identify additional environmental variables that may contribute to higher levels of forecasting skill. Results suggest that pesticides are unlikely to influence distributions, whereas ocean warming and acidification may have increasing impacts into the future.

Fourth, relationships have been identified between local environmental conditions and the occurrence of Irukandji stings. The current work has extended previous work on predicting Irukandji stings by developing a modelling framework and extending the analyses to regions throughout the GBR. Both winds and tides have been shown to be useful predictors, with important geographical and seasonal variations. The current work also confirms that the primary season for Irukandji stings is December to April or May, but is shorter on Whitsundays Islands and Reefs.

Wind direction has been shown to be important for all beaches on the Great Barrier Reef, with most areas having more stings during north-westerly winds and fewer stings during south-easterly winds. This is the strongest predictor of stings in the region. Slow wind speeds also led to more Irukandji stings, particular in the Cairns region for Beaches, Islands and Reefs. More Irukandji stings were also found during slower wind speeds on Townsville Beaches.

Tide was found to be important, particularly Tidal Height, with more Irukandji stings around low tide. There were also more stings in most areas with an incoming tide. Tidal range was important in some regions, but greater tidal range led to more stings in some regions and fewer stings in other regions.

Cairns Beaches have the highest number of reported Irukandji stings and they are the most predictable area. The study by Gershwin et al. (2014) investigated the impact of wind on Irukandji stings at Palm Cove. They did not use a statistical modelling approach, but found that a decline in wind speed led to Irukandji stings. We found similar results for Cairns Beaches, but extended the analysis to wind direction and tidal variables.

From an ecological perspective, the preference of Irukandji for weaker north-westerly or south-westerly winds might be explained in terms of avoidance of potentially damaging water turbulence and onshore transport within the deeper water (Gershwin 2014). A higher

prevalence of stings around low tide has not previously been reported and the underlying mechanism is still unclear. The turn of the tide may also be a period of lower currents and water turbulence, but this should also be true around high tide.

The models can only explain a relatively small amount of the variability, indicating that other confounding factors may also influence the presence or absence of Irukandji in a particular area on a particular day. For example, preliminary field testing at Palm Cove in December 2017 and January 2018, involving twice daily sampling over a 17-day period, predicted a high risk of Irukandji over the period 4-6 January due to low wind conditions. On 4 January, *Carukia barnesi* was observed in significant numbers as forecast and accompanied by oceanic species such as salps, *Liriope*, *Ocyropsis*, and *Solmaris* typically associated with Irukandji (Stenning 1928, Barnes 1964). However, on 5-6 January, there were no Irukandji or salps found, despite the prevalence of the other oceanic indicator species. Clearly there were confounding physical or biological factors present that are not captured by the model.

When implemented, the proposed forecasting system will estimate the relative risk of Irukandji stings based on historical statistical patterns. In this context, it is important to recognise that forecasting high sting risk is not the same as forecasting that Irukandji will be present or that stings will occur (in the same way that forecasting extreme fire risk is not the same as forecasting that there will be a fire). There is a higher likelihood that Irukandji will be present on high risk days, but it is expected that Irukandji will be absent on some high-risk days (as occurred on the 5-6 January 2018) and equally that Irukandji may be present on some low-risk days.

The risk of Irukandji stings is dependent on the likelihood of an interaction between humans and Irukandji, and therefore will tend to increase if either the number of swimmers or the number of Irukandji increases. For most beaches, the number of swimmers is consistently high and we would expect stings almost anytime an Irukandji infestation is present (and beaches are not closed). However, for less frequented reefs, the number of stings will depend strongly on the coincidence of swimmers and Irukandji. In this case, including a measures of reef visitation could significantly improve the model and associated forecasts.

5.0 RECOMMENDATIONS AND CONCLUSION

The predictability of Irukandji varies across regions and there is clearly potential to improve forecasting in all regions. Continued development of the AVJD will be critical, particularly in reef and island areas where the existing data is quite limited. This process could be accelerated through routine sampling and/or near real-time camera surveillance, which would both improve predictions and support their ongoing validation.

The underlying models can also be improved through identification of other relevant environmental drivers using laboratory studies, and by accessing relevant new data streams. For example, incorporating information on reef visitation (or related proxies) could lead to significant improvements in Irukandji predictability in some regions.

In regions such as Cairns beaches, there is already good data coverage and the model explains a relatively high percentage of the variance. It is recommended that pilot forecasting systems should be implemented in such regions. An automated system could regularly access the Bureau of Meteorology's weather forecasting services for information on winds and tides, which could then be converted into forecasts of Irukandji risk up to a week in advance. This would allow stakeholders to more effectively plan their operations. For example, during high risk periods, life savers could increase the frequency of their net sampling and plan for likely beach closures, while marine tourism vessel operators could potentially target lower risk areas on the reef.

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APPENDIX 1: PUBLIC DATABASE DESCRIPTION

Dataset title

Venomous Jellyfish Database data extraction - October 2017 (NESP 2.2.3, CSIRO)

Dataset Authors

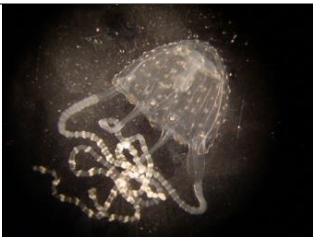
Gershwin, Lisa-ann, Dr (Research Scientist) – Principle investigator
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Preview images

Image name	Attribution	Caption
 Irukandji adult DSCN1652-Lisa-ann Gershwin CC.jpg	Lisa-ann Gershwin	The Irukandji jellyfish <i>Carukia barnesi</i> . This specimen was approximately 1 cm in bell height and was photographed under a dissecting microscope.

Summary of what this dataset describes and where it is relevant?

Venomous Jellyfish Database download (October 2017)
This dataset contains one Microsoft Excel file of publicly available data contained in the Venomous Jellyfish Database. The file contains 265 sting events along the North Queensland coast from December 1998 to March 2017.

Background information, purpose and lineage

Venomous Jellyfish Database download (October 2017)

This extract from the Venomous Jellyfish Database was made for eAtlas as part of the 2.2.3 NESP Irukandji forecasting system project.

It contains jellyfish sting and specimen information. Data were compiled from numerous sources (noted in each record), including:

- Lisa-ann Gershwin
- Media reports

These data will be used as part of the Irukandji forecasting model.

This download contains data that is publicly available.

Methods

This data set contains information on sting events and specimen collections that have occurred around Australia, which involved venomous jellyfish (Irukandji syndrome-producing species in the genera *Carukia*, *Malo*, *Morbakka*).

These data were collected over numerous years by Lisa-ann Gershwin from various sources (primarily media). These data were entered into an excel spreadsheet, which formed the basis of the Venomous Jellyfish Database. This database was developed as part of the 2.2.3 NESP Irukandji forecasting system project.

Some data have been standardised, e.g., location information and sting site on the body. Data available to the public have been approved by the data owners, or came from a public source (e.g. newspaper reports, media alerts).

Limitations of the data

Venomous Jellyfish Database download (October 2017)

This data shows the occurrence of reported jellyfish stings and specimens along the North Queensland coast. It does not provide a prediction of where jellyfish or jellyfish sting events may occur.

These records represent a fraction of known sting events and specimen collections, with more being added to the list of publicly available data as permissions are granted.

Historical data dates may be coarse, showing month and year that the sting occurred in. Some events have date only.

Format of the data

Venomous Jellyfish Database download (October 2017)

This dataset consists of one Microsoft excel file containing information on jellyfish events along the North Queensland coast.

eAtlas_extract_event_20171018.xlsx

Data Dictionary

Venomous Jellyfish Database download (October 2017)

eAtlas_extract_event_20171018.xlsx

Column name	Data type	Comments
CSIRO_ID	number	Unique id
EVENT_TYPE	varchar2	Type of event – sting or specimen
STATE	varchar2	State in which event occurred
REGION	varchar2	Broader region of State the event occurred in
LOCAL_GOV_AREA	varchar	Local government area that the event occurred in – if known
MAIN_LOCALITY	varchar	Main locality that the event occurred in
SITE_INFO	varchar2	Site details/comments
YEAR	date	Year event occurred
MONTH	date	Month event occurred
DAY	date	Day of the month the event occurred
EVENT_TIME	date	Time the event occurred HH24:MI If time is unknown then NULL
EVENT_RECORDED	varchar2	time/date event reported e.g. early afternoon, morning, on weekend
EVENT_COMMENTS	varchar2	Comments about the event
LAT	number (8,6)	Latitude in decimal degrees
LON	number (8,6)	Longitude in decimal degrees
LOCATION_PRECISION	varchar2	How accurate the location is
EVENT_OFFSHORE_ONSHORE	varchar2	Where the event occurred (if known) – beach, island, reef
LOCATION_COMMENTS	varchar2	Comments relating to the location of the event
WATER_DEPTH_M	number	Depth of water, in metres, that the event occurred in (if known)
AGE	number	Age of patient if known
SEX	varchar2	Gender of patient if known
HOME	varchar2	Home state/county of patient
HOSPITAL	varchar2	Hospital the patient was treated at (if known)
STING_SITE_REPORTED	varchar2	Reported sting site on the body
STING_SITE_BODY	varchar2	Standardised area on body that sting was reported – upper limb, lower limb etc.
NUMBER_STINGS	number	Number of stings recorded, if known
VISIBLE_STING	varchar2	The nature of visible sting marks, if reported
PPE_WORN	varchar2	Was Personal Protective Equipment (PPE) worn?
PATIENT_COMMENTS	varchar2	Comments about the patient
TIME_TO_ONSET	varchar2	Delay between sting and onset of symptoms, if reported
PATIENT_CONDITION	varchar2	State the patient was in, e.g. distressed, calm, stable
BLOOD_PRESSURE	varchar2	Comments relating to blood pressure of the patient
NAUSEA	varchar2	Did the patient experience nausea and/or vomiting?
PAIN	varchar2	Location and/or intensity of pain experienced by the patient
SWEATING	varchar2	Did the patient experience sweating?
TREATMENT	varchar2	What treatment the patient was given
DISCHARGED	varchar2	When the patient was discharged from hospital
ONGOING_SYMPTOMS	varchar2	What ongoing symptoms the patient is experiencing
NEMATO_SAMPLES	varchar2	Were nematocyst samples taken?
SPECIES_NAME	varchar2	Species name, if determined
PATROL	varchar2	Was the sting on a patrolled beach
CURATOR	varchar2	Where the data came from e.g. Gershwin = Lisa-ann Gershwin
DATA_CODE	varchar2	Access constraint on data
REFERENCE	varchar2	Source of the information for event
ENTERED_BY	varchar2	Who entered the data
ENTERED_DATE	date	When the data was entered

Temporal extent

Start date:	26/12/1998	End date:	16/03/2017
-------------	------------	-----------	------------

Spatial Extent

	(decimal degrees)	(decimal degrees)	(decimal degrees)	(decimal degrees)
Great Barrier Reef, Queensland	-10.00	-20.2342	141.8459	149.025

References

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Declaration

I certify that I am the owner or creator of the submitted dataset and understand that the submitted dataset will be released publicly under a [creative commons attribution 3.0 Australian license](#) (contingent on restrictions applied in Question 13).

Project:	2.2.3 NESP Irukandji forecasting system project		
Submitted by:	Linda Thomas	Date:	18/10/2017

Non eAtlas dataset hosting

Is this dataset already hosted in an institutional repository?	Yes
If yes: What is the name of the repository and a URL to where the data is available from?	Venomous Jellyfish database. Not available online

Restrictions on raw data

Only open source data has been supplied in this download.
Other data held in database has publication restrictions placed on it.

Delayed data publication

Is there a reason for delayed publication of this dataset?	No
If so why and what date can it be published?	

Additional licensing information

This database is based on the "Irukandji Sting Database" assembled and curated by Dr Lisa-Ann Gershwin of the Australian Marine Stinger Advisory Services, and others, and enhanced by CSIRO. Derivative products and copies of this work must display this acknowledgement:

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