Dangerous jellyfish blooms are predictable

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The potentially fatal Irukandji syndrome is relatively common in tropical waters throughout the world. It is caused by the sting of the Irukandji jellyfish, a family of box jellyfish that are almost impossible to detect in the water owing to their small size and transparency. Using collated medical records of stings and local weather conditions, we show that the presence of Irukandji blooms in coastal waters can be forecast on the basis of wind conditions. On the Great Barrier Reef, blooms largely coincide with relaxation of the prevailing southeasterly trade winds, with average conditions corresponding to near zero alongshore wind on the day prior to the sting. These conditions are consistent with hypotheses long held by local communities and provide a basis for designing management interventions that have the potential to eliminate the majority of stings.

1. Introduction
Irukandji are small transparent jellyfish (figure 1a) that cause the potentially fatal Irukandji syndrome [1–4]. Their stings produce debilitating illness, with some patients requiring life support and a significant number experiencing recurring symptoms [5–8]. At least 14 Irukandji species are known, and stings have been confirmed throughout coastal, reef, and island tropical and subtropical waters globally [9–12] and may increase further with climate change [13]. While most stings remain undiagnosed, particularly in the developing world [10–12], reported hospitalizations in Australia are typically 50–100 per year. The financial impact on tourism and the practical safety implications for marine-based industries, such as fisheries and commercial diving, can be enormous [4,14]. For example, the costs of cancelled tourism bookings following two fatalities on the Great Barrier Reef in 2002 have been estimated to be in excess of $US65M [12].

Anecdotal accounts from lifeguards and other beach-users over many years raised the hypothesis that stings coincide with periods of low northeasterly wind. In this interdisciplinary study, we combine medical and environmental data to test this hypothesis and demonstrate significant capacity in forecasting Irukandji blooms.

2. Material and methods
The northern Great Barrier Reef coastline was selected as the focus for the study as it is a major hotspot globally for documented Irukandji stings. We related sting data that we obtained from hospital and ambulance records (sting times and locations) to local model winds within the period January 1985–August 2012 (see appendix in electronic supplementary material). Wind estimates were obtained from the European Reanalysis (ERA-Interim) model produced by the European Centre for Medium-Range Weather Forecasts [15]. These winds were selected on the basis that for any future applications comparable products are available globally as part of routine weather prediction services. However, very similar results were obtained when winds from a local meteorological station (Cairns airport) were used in the analysis (not shown).
Sting data included primary information such as date, time of day and locality of stings, as well as secondary details such as age and gender of the sting victim, where on the body they were stung, their activity at the time of the sting and their general medical condition. While the sting database is almost certainly the most comprehensive available for anywhere in the world, there are extended periods during which stings were not recorded. Sting data are also not a perfect indicator of the presence of Irukandji. For instance, no stings may occur during a bloom event due to low beach usage at the time. We have thus focused our analysis on conditions leading up to and immediately following recorded sting events.

For each sting event, we defined time zero as the time of the sting and then compiled hourly time series extending both backward and forwards 16 days. These time series included both the alongshore wind component (the coastline runs approximately northwest to southeast and southeasterly winds were designated as positive) and the cross-shore wind component (southwesterly offshore winds designated as positive). Wind data around all sting events (82 when ignoring multiple stings on any single day) could then be plotted on a single time axis, from which time series of the average and median values were calculated. Data for the various events were then combined by calculating averages, medians, and 25th and 75th percentiles for the two wind components across all 32-day time series.

The second stage of our analysis looked at how effective the use of wind data would have been in reducing sting rates over the historical period. Management interventions (e.g. mandatory protective clothing or short-term closure of beaches) were assumed to be triggered by a fixed threshold in the alongshore wind component. We varied the wind threshold for intervention (south-easterly component dropping to 1.0, 0.0 or $-1.0 \text{ m s}^{-1}$) and the length of time the intervention was left in place (1–5 days). In all cases, it was assumed that there were no stings while the intervention was in place. Results are summarized by a $\chi^2$ analysis and then graphically in terms of the trade-off between the percentage reduction in days that stings would have occurred and the percentage of days affected by the management intervention.

### 3. Results

Most Irukandji stings occurred during summer (December–February), when southeasterly trade winds (alongshore) tend to be less persistent (figure 1b). When we compared
and other industries to move to safer areas or defer work where possible.

All days from November to May and all beach, island and reef locations are currently treated for management purposes as equally moderately high risk for Irukandji stings. This has proved to be frightening for tourists and costly for the tourism industry. We have demonstrated in our study area that days associated with a prolonged weakening of trade winds are higher risk than the majority of days in which normal trade wind conditions prevail. While the primary purpose of developing a forecasting system is to provide an early warning to reduce stings, an important outcome is also to identify which days and locations are lower risk.

Our results have led us to develop a hypothesis about the biophysical processes that drive Irukandji blooms in near shore environments. This hypothesis relies on a number of assumptions relating to the life cycle of Irukandji, which is poorly known. For example, beyond the shallow near shore zone, there are no direct observations of their distribution geographically or through the water column [4]. A week-long metamorphosis suggests that they are already metamorphosed prior to weakening of the trade winds (i.e. wind changes are not the trigger). Indeed, half-grown specimens and mature adults in the same samples indicate that metamorphosis is likely to be continuous [4]. While the occurrence of stings at offshore reefs suggests a broad distribution across the continental shelf, juveniles with remnant umbilical cords in samples suggest that there are also breeding grounds close to shore. Our hypothesis is therefore developed on the assumption that Irukandji are for the most part resident offshore (at least beyond normal recreational swimming depths) and that metamorphosis is continuous (at least throughout the sting season).

Under typical trade wind conditions, turbulent kinetic energy is high throughout the ocean surface mixed layer, and there is a mean downwelling flow (onshore near the surface and offshore at depth). Under these prevailing conditions, we would expect that any Irukandji medusae swimming up into the water column would be carried further offshore (figure 2a) and to the north. While they could return shoreward by swimming into the surface onshore flow (figure 2a), anecdotal evidence suggests that when buffeted by turbulence Irukandji tend to stop swimming and sink [4], a response that has been well documented in other types of jellyfish [16]. Switching between swimming and sinking may help Irukandji retain their position on the inner shelf by recirculating [17] or they may simply find shelter near the seabed. In any case, their absence in the near shore environment under downwelling conditions (as evidenced by the rarity of stings) seems to confirm that they spend limited time near the surface under trade wind conditions.

As the trade winds weaken, turbulence decreases and the thermocline (that was previously pulled downward near the coast by downwelling flows) relaxes towards a more horizontal state. This relaxation process moves deeper water onshore as a cold intrusion (balanced by offshore flow at the surface), carrying any Irukandji in their pelagic phase offshore (figure 2b). Such intrusion events in the Cairns region have been estimated to carry $0.15-1.5 \times 10^8$ m$^3$ of water (per longshore metre of shelf) within a bottom intrusion of depth around 15 m [18], corresponding to cross-shelf excursions of 10–100 km consistent with earlier estimates of 30–100 km based on measured current velocities [19]. These large events would be capable
of transporting Irukandji across most of the shelf width; however, much smaller events are more common and would be sufficient to transport Irukandji from inner-shelf habitats. If this process continued indefinitely, then Irukandji would tend to be carried offshore again as they approached the surface (figure 2b). However, this flow decays as the thermocline equilibrates, leaving other processes such as the northeasterly seabreeze and flood-tide excursions (2–5 km, [19]) to carry Irukandji into shallow water (figure 2c). This scenario is broadly consistent with our empirically observed relationship between weakening of the trade winds and the appearance of coastal Irukandji blooms, although further field sampling of Irukandji under a range of oceanographic conditions will clearly be required to test details of the underlying hypothesis.

Our model assumes that medusae would be actively staying below the turbulent zone until the waters become more favourable for these delicate hunters [4]. This trigger cannot occur in the polyp phase because of the delay associated with metamorphosis (ca 7 days). Similarly, complex movements have been demonstrated for other species of jellyfish [20–23] and should be tested for Irukandji. A variety of methods are currently in use to assess jellyfish movement patterns, including particle tracking models [23] and direct measurements of currents [24] and are likely to prove informative towards refining our knowledge of the influence of winds on stinging incidence.

Our results demonstrate the value of local knowledge in generating scientifically testable hypotheses. While the long-believed, locally observed correlation with northeasterlies is indirectly supported by our results, it is the associated weakening of the southeasterlies that offers a longer, more robust forecasting ability. We anticipate our findings will lead to the development of technologies for delivery of improved public and occupational safety objectives, e.g. making forecasts publicly available via the web, radio, SMS or smartphone apps. Moreover, since the underlying oceanographic processes are widespread, this approach is likely to be applicable in reef and island localities, as well as other regions of the world, where there are Irukandji.

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