Temporal and spatial characterization of acoustic activity patterns of Indo-Pacific humpback dolphins (*Sousa chinensis chinensis*) in Hong Kong waters

By

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Abstract

Indo-Pacific humpback dolphins face a number of serious anthropogenic pressures in Hong Kong waters. Since the late 1990's, data has shown both a decline in their abundance and shift in their distribution, therefore obtaining a better understanding of their habitat use through passive acoustic monitoring is important. Twelve C-PODs deployed throughout their habitat from June 2018-July 2019 were able to provide data on diel, seasonal and geographical patterns in their acoustic activity; and location had the largest effect on the probability of detections. When acoustic and visual data were compared to characterize the ability of the C-PODs to detect dolphins and assess the relative efficacy of each detection method, little overlap was found between methods. Despite these limitations, the C-PODs are able to survey continuously and simultaneously over many areas and represent a valuable tool for long-term monitoring.

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General Introduction

1. *Sousa* spp. - Humpback dolphins

Humpback dolphins (*Sousa* spp.) are robust, medium-sized delphinids found in estuarine and shallow coastal waters of the western Pacific, Indian and eastern Atlantic oceans, see **Figure 1** (Jefferson & Smith, 2016). Four species are recognized in the Genus *Sousa*: the Atlantic humpback dolphin, S*ousa teuszii*; the Indo-Pacific humpback dolphin, *Sousa chinensis*; the Indian Ocean humpback dolphin, *Sousa plumbea*; and the Australian humpback dolphin, *Sousa sahulensis* (Jefferson & Rosenbaum, 2014).

Indo-Pacific humpback dolphins, *Sousa chinensis*, are found in Southeast Asia from Myanmar to central China and the Indo-Malay Archipelago (Jefferson & Karczmarski, 2001). Two subspecies have been described: the Taiwanese humpback dolphin, *Sousa chinensis taiwanesis*, which is endemic to the waters of western Taiwan, and the Chinese humpback dolphin, S*ousa chinensis chinensis*; the nominate subspecies (Wang et al., 2016). Their use of shallow (<20m) coastal waters and preference for estuarine waters makes them particularly vulnerable to a large number of anthropogenic activities (Jefferson & Karczmarski, 2001). The total global abundance of individuals within this species is estimated to be no greater than 16,000 individuals, with several populations known to be declining (Jefferson & Smith, 2016). The International Union for Conservation of Nature (IUCN) listed the Chinese humpback dolphin, *Sousa chinensis chinensis,* as Vulnerable and the Taiwanese humpback dolphin, *Sousa chinensis taiwanensis,* as Critically Endangered (Jefferson & Smith, 2016; Wang et al., 2016).

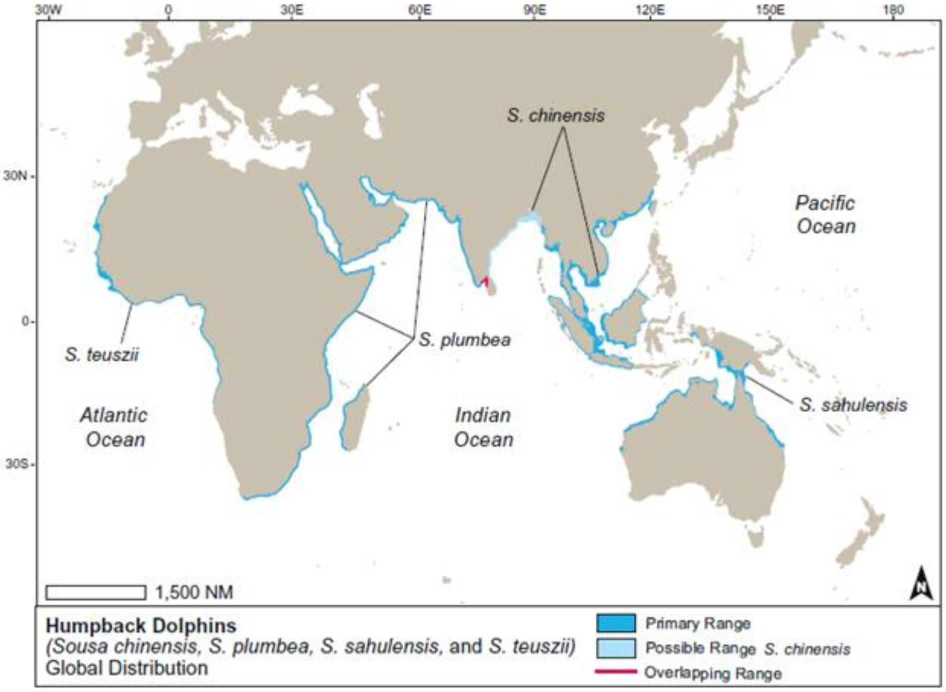

Figure 1: Map of global distribution of the four species in the genus *Sousa*. Figure from Würsig et al. (2018).

1.1. *Sousa chinensis chinensis* in Hong Kong

In Chinese waters, eight populations of humpback dolphins have been identified (Jefferson & Hung, 2004). The Pearl River Estuary (PRE) population is the most well-studied and largest population, with approximately 2,500 animals (Chen et al., 2010; Jefferson et al., 2012). The PRE consists of the waters of Macau, Hong Kong and the People's Republic of China (see **Figure 2**) (Jefferson & Hung, 2004). Recently, it has been suggested that the Moyang River Estuary (MRE) should also be included as part of their distribution, and that it be renamed the PRE-MRE population due the movement of individuals between locations (Li et al., 2019).

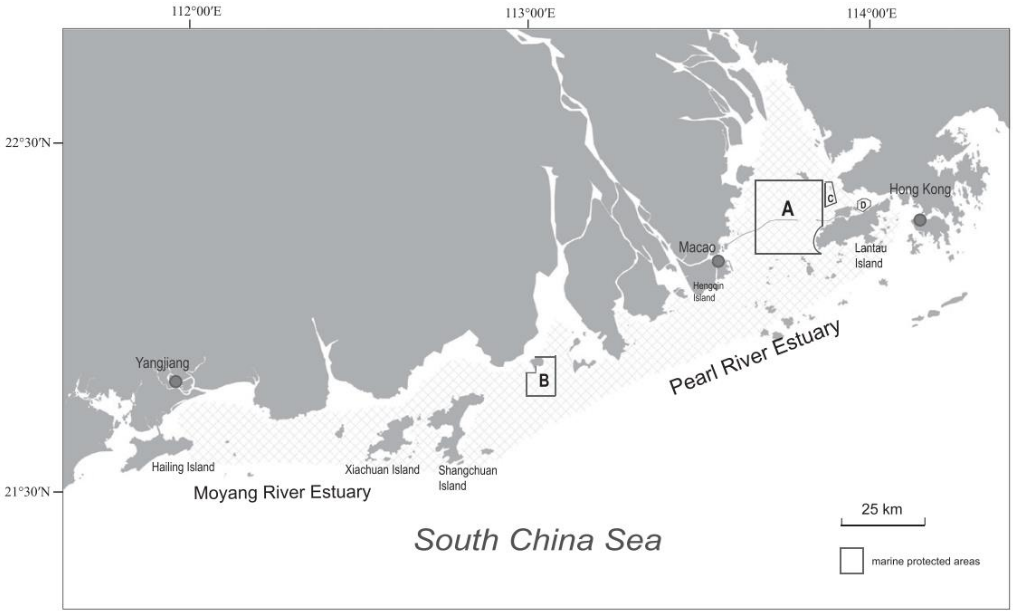

Figure 2: Map of the Pearl River Estuary (PRE) and Moyang River Estuary. The lettered boundaries are existing marine protected areas: A, Guangdong Pearl River Estuary Chinese White Dolphin National Nature Reserve; B, Jiangmen Chinese White Dolphin Provincial Nature Reserve; C, Sha Chau and Lung Kwu Chau Marine Park; and D, The Brothers Marine Park. Figure from Li et al. (2019)

In Hong Kong waters, *Sousa* are primarily sighted around Lantau Island (see **Figure 3**). There is evidence of a decline in *Sousa* using Hong Kong waters over the last decade (Jefferson et al., 2009; Würsig et al., 2016). It is currently unclear if this is due to a declining population size, or to individuals emigrating to other areas (Würsig et al., 2016). In addition to a decline in numbers of *Sousa*, a shift in their distribution patterns has also been seen which is likely influenced by coastal development and the large number of human activities in the area.

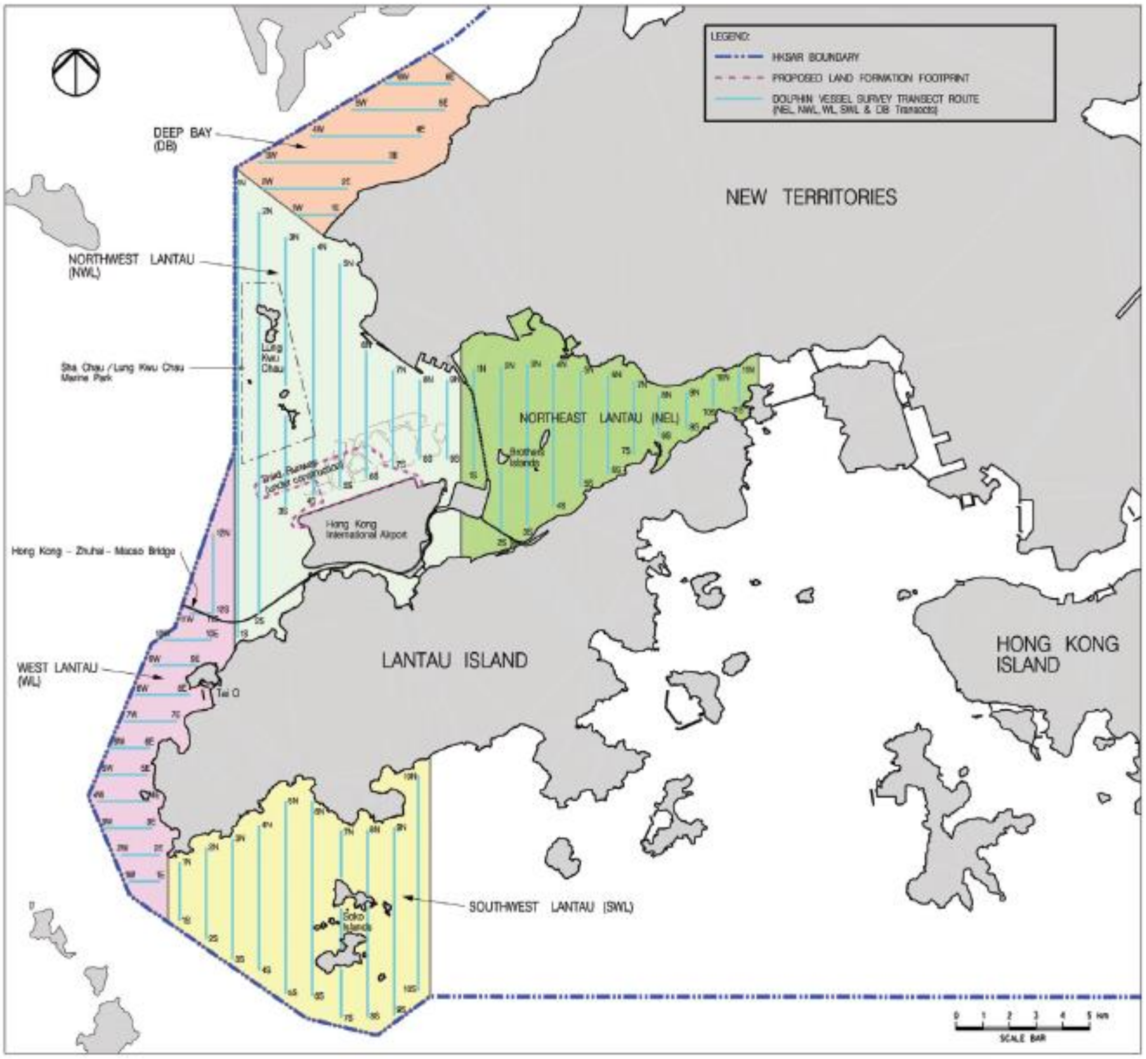

Figure 3: Map of main survey areas (with transect lines) in Hong Kong's waters. Figure from Jefferson (2018).

Coastal development in Hong Kong has rapidly increased over the past 20 years in relation to the economic growth in Southeast Asia and China in particular. It also remains one of the busiest ports in the world. The largest threats to the Hong Kong *Sousa* population have been identified as: habitat loss due to land reclamation, habitat degradation due to chemical and acoustic pollution, and anthropogenic mortalities from transport and construction vessel traffic as well as fishery activities (Jefferson et al., 2009). For example, major development projects such as the construction of the Hong Kong-Zhuhai-Macau Bridge (HKZMB) and expansion of the Hong Kong International Airport (HKIA) (see **Figure 3**) affected the area and underwater soundscape with dredging, filling and pilling in addition to increased vessel traffic (Jefferson et al., 2009; Pine et al., 2017; Sims et al., 2012). High-speed ferry traffic has also increased with the SkyPier service running over a 120 trips a day in addition to more daily trips using the Ursmton Road, a large shipping passage between northern Lantau Island and the New Territories to the PRE. The channels running around Southern Lantau waters including traffic between Hong Kong and Macau have also increased. Studies have shown that these activities are influencing the dolphins (e.g., altering diving times and behavioural states), and are likely causing a shift in their habitat use patterns, such as avoiding areas of high human traffic that had previously been areas of high dolphin density (Nowacek et al., 2007; Piwetz et al., 2012).

Data from the latest year of line-transect data present some startlingly low numbers (Hung, 2019). For example, 2018-2019 marked the lowest combined estimate of dolphin abundance (n=32) in the four main survey areas (Southwest Lantau, West Lantau, Northwest Lantau and Northeast Lantau) in Hong Kong waters (see **Figure 3**) (S. K. Hung, 2019). Similarly, the lowest level of dolphin calf occurrence (1.5%) and the lowest percentage of socializing activities (2.5%) since 2002 in addition to very low mean dolphin group size in Northwest Lantau were also recorded this past year (Hung, 2019). Overall, dolphins were most frequently sighted along western Lantau while the North Lantau region continues to show no signs of recovery after the completion of the HKZMB (Hung, 2019). **Figure 4** shows the changes in distribution patterns over the last six years, where it is evident that the dolphin sightings in northern Lantau Island have been greatly reduced, with visible but less dramatic declines in other areas.

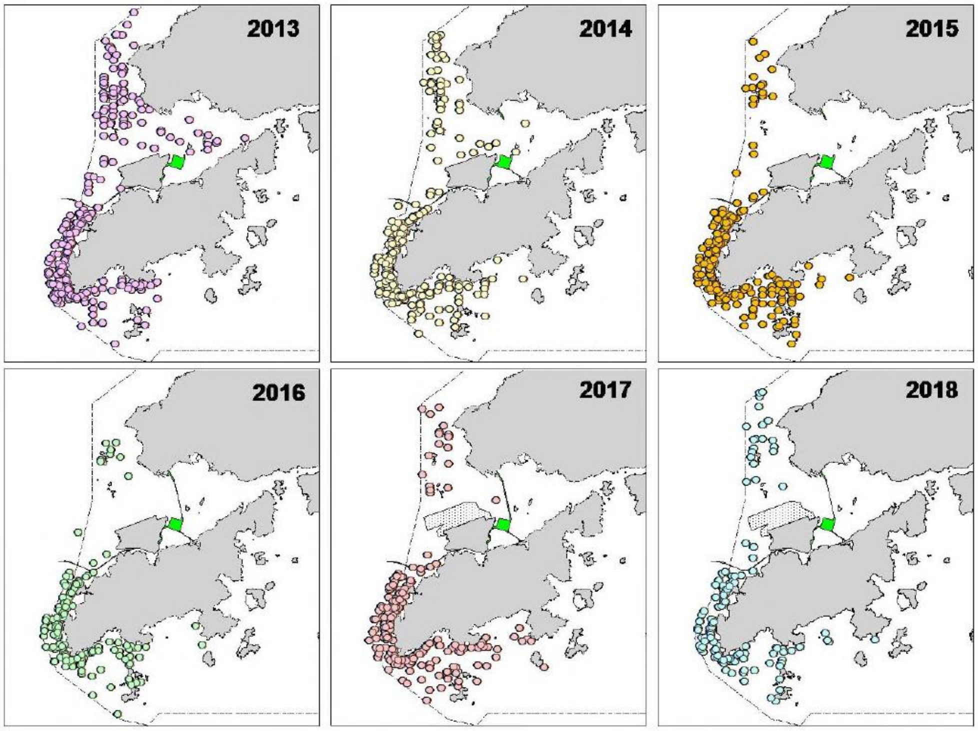

Figure 4: Dolphin distribution patterns from 2013-2018. Figure from Hung, 2019.

To help conserve humpback dolphins in Hong Kong's waters for the long-term, the Agriculture, Fisheries and Conservation Department (AFCD) of the Hong Kong Government has designated two marine parks in dolphin habitat: the Sha Chau and Lung Kwu Chau Marine park (SCLKCMP) and the Brothers Marine Park (BMP). Both of these are located in the Northern Lantau Island region see **Figure 5** (Hung & Wang, 2018). Within the marine parks, only commercial fishing with a permit is allowed, harmful fishing methods are restricted and vessel speed is limited to 10 knots. SCLKCMP was established in 1996 and identified as critical habitat for *Sousa* in Hong Kong, but there has been a decline in dolphin occurrence there in recent years (Hung & Wang, 2018). BMP was established in 2016 to aid the recovery of dolphins after the HKZMB completion, because it appeared dolphins had largely vacated the area since 2015 (Hung, 2019; Hung & Wang, 2018).

In addition to these existing parks, two additional marine parks were recently proposed, the Southwest Lantau Marine Park (SWLMP) and the South Lantau Marine Park (SLMP). In 2017, the southwestern and southern Lantau Island areas were recognized as important for the dolphins and other marine resources. It should be recognized that these marine parks were put in place for political reasons and not biological. These MPA's are very small areas and do not facilitate any protection for movement between areas in addition to it not encompassing the most important dolphin habitat (entire Southwestern coast of Lantau Island) remains unprotected (Jefferson, 2018). Therefore, there is a call for an interconnected matrix of MPA's to adequately protect humpback dolphin habitat in Hong Kong (Jefferson, 2018; Karczmarski et al., 2016).

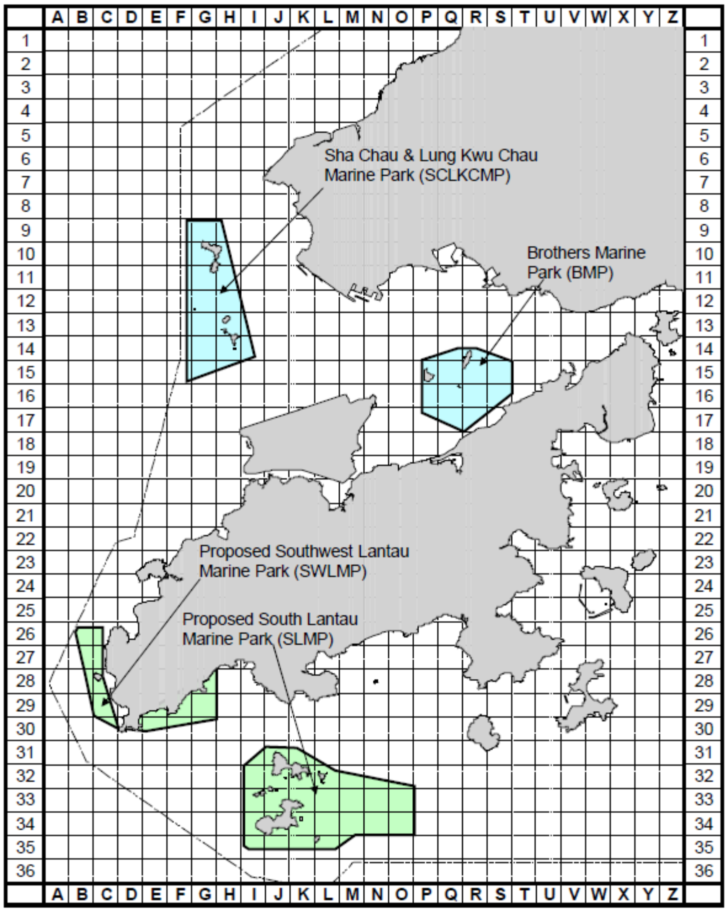

Figure 5: Map of existing (blue) and proposed (green) marine parks. Figure from Hung, 2019.

2. Passive Acoustic Monitoring (PAM) and Cetaceans

The majority of data on the distribution and habitat use patterns of cetaceans (whales, dolphins, and porpoises) has been based on observational data (from land, vessel, or aerial platforms). Although extremely useful and informative, these data are limited to the small proportion of the animals' lives when they are visible above the water surface, such as during daylight hours, in good weather, and when the field teams are conducting surveys (Tregenza et al., 2016). Recent advances in passive acoustic monitoring (PAM) technology provide attractive non-invasive methods to study these animals by simply recording the identifiable sounds they produce (Marques et al., 2013; Roberts & Read, 2015). Odontocetes (toothed cetaceans) produce three main types of sounds: broadband clicks, tonal whistles and burst-pulse sounds (Morisaka, 2012). Clicks are short broadband sounds used for echolocation to aid orientation in their environment and to locate prey (Morisaka, 2012; Tregenza et al., 2016). Whistles are narrowband pure-tonal sounds with a vast range of frequencies between species that are used for communication and social cohesion (Morisaka, 2012). Burst-pulse sounds tend to have lower frequencies than the other sounds and very short inter-pulse intervals (Morisaka, 2012). Humpback dolphin clicks were found to extend up to at least 200 kHz (Goold & Jefferson, 2004). Whistles and rapid click trains were found to be highly variable with a frequency range of 1 to 115 kHz and lasting 0.03 to 3.85 seconds (Sims et al., 2012).

Today, multiple PAM tools currently exist using hydrophones with varying deployment methods. The instruments can be fixed (e,g POD), drifting (e.g sonar buoys) or mobile (gliders, boats) (Tregenza et al., 2016). These have the advantage of being able to record sounds 24 hours a day, 365 days a year, regardless of the amount of daylight and weather conditions.

2.1 Cetacean Porpoise Detectors (C-PODs)

Cetacean Porpoise Detectors (C-PODs), made by Chelonia Ltd. (Cornwall, UK) are small autonomous PAM devices, typically fixed or moored in the water column, that log acoustic activity in the form of echolocation signals. CPODs are able to detect all odontocetes (dolphins, toothed whales, and porpoises), other than sperm whales (*Physeter macrocephalus*), whose clicks fall below the C-POD's 20 kHz to 160 kHz frequency range of detection. (Chelonia Ltd., 2018). The effective detection range (EDR) is estimated to be between 400-1000 metres, with a smaller EDR for porpoise clicks than for those of dolphins (Chelonia Ltd., 2018; Garrod et al., 2018; Nuuttila et al., 2018; Roberts & Read, 2015). Although digitised sounds are not stored, CPODs record the time of occurrence, centre frequency, intensity, duration, bandwidth and frequency of tonal clicks within the frequency range (Chelonia Ltd., 2018).

CPODs are unaffected by light and weather conditions and have the ability to log continuously for extended periods. This makes them particularly useful for collecting data on species that are difficult to study visually and/or that may have different habitat use patterns in periods of daylight versus the night (Heenehan et al., 2017; Jaramillo-Legorreta et al., 2017; Leeny et al., 2011; Verfu et al., 2006). As a result, CPODs have provided a wealth of information, across a range of species, on habitat use throughout a number of different scales such as diel, seasonal and geographic (Gallus et al., 2012; Rayment et al., 2011; Todd et al., 2009; Verfu et al., 2006). CPODs are also able to contribute some data on the behavioural states of the animals through the patterns of the click profiles (e.g., feeding click-trains) (Todd et al., 2009; Tregenza et al., 2006, 2007).

3. Significance of Research

Given the dramatic decline in *Sousa* numbers in Hong Kong waters, and the extent of coastal development, there is a need for more comprehensive data regarding how dolphins are using these waters and how that has changed over time. Such data can be used to test for potential relationships between anthropogenic activities and changes in patterns of dolphin habitat use. Information gained from such analyses can then be used to inform Environmental Impact Assessments (EIAs) for proposed development in the future. PAMs are ideal for obtaining such information because they can provide data on dolphin presence/absence in different areas throughout the habitat and at times when visual surveys are not possible. The goal of my thesis is to use C-PODs to characterize Indo-Pacific humpback dolphin acoustic activity in Hong Kong waters across space and time.

First, I will assess if any diel, seasonal and geographic acoustic activity patterns exist to identify when and where the dolphins are spending their time, and how these change through time and space (Chapter 2). This will be done using a full year of data from 12 C-PODs deployed around Lantau Island (see **Figure 6**). Four of these locations are within the two established marine parks, six are in the two proposed marine parks in the south and two are in high dolphin density areas.

Second, I will compare the acoustic data to the sighting data from vessel surveys to estimate the effective detection range of the CPODs, and to compare the relative ability of each method to detect dolphins (Chapter 3). This information will help identify the relative efficiency of each method, and inform future decisions regarding what method(s) are most appropriate for monitoring this population.

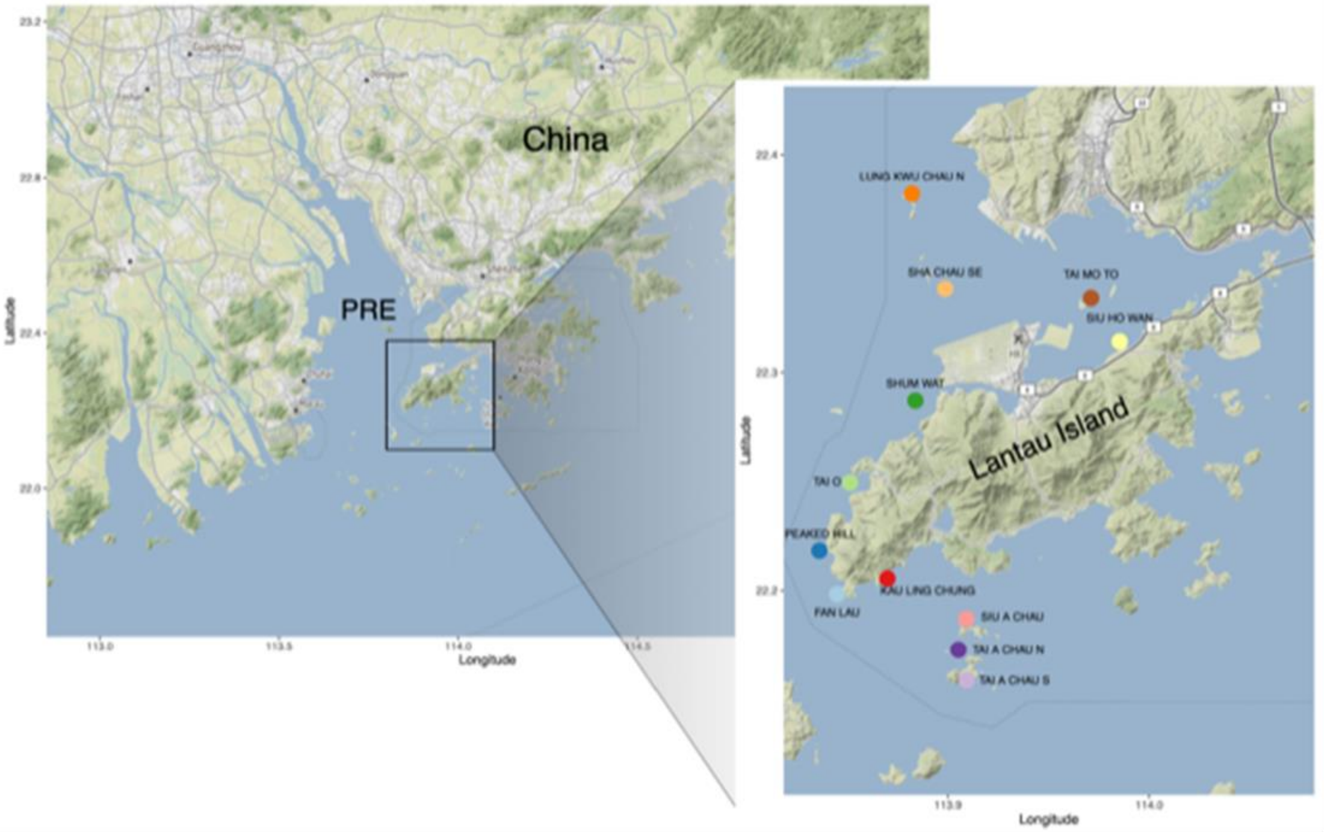

Figure 6: Maps showing study area. PRE stands for Pearl River Estuary. C-POD locations are shown by coloured dots on the inset map. Dotted line around Lantau Island represents Hong Kong boundary. Maps made with ggmap function in R (Kahle & Wickham, 2013).

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CHAPTER 2

Quantification and characterization of acoustic activity patterns of Indo-Pacific humpback dolphins (*Sousa chinensis chinensis*) in Hong Kong waters

Abstract

Indo-Pacific humpback dolphins in Hong Kong waters (*Sousa chinensis chinensis*) face a number of serious anthropogenic threats. Evidence of a decline in dolphin abundance, as well as a shift in their distribution, in these waters has been noted in recent years. Since 1995, this population has been studied extensively using visual surveys. To supplement these long-term visual surveys, twelve C-PODs—which log acoustic activity in the form of echolocation signals—were deployed throughout the area from June 2018-July 2019. I analyzed the data collected from these C-PODS to quantify and characterize the acoustic activity of humpback dolphins in Hong Kong waters, and to assess their diel, seasonal, and geographic patterns. Location had the largest effect on detection probabilities, with vast differences in the number of detections across locations. These ranged from 34,739 detections in these twelve months at Peaked Hill (the location with the most detections) to 168 detections at Tai Mo To. The proportion of acoustic detections at each location coincided well with those from visual surveys, although some dolphins were detected acoustically in areas that did not have sightings during this same time period. Seasonal and diel periods also had clear impacts on acoustic detection probabilities, but these relationships differed across locations. Combined, these data indicate substantial heterogeneity in the degree to which humpback dolphins use different areas within Hong Kong waters, and also substantial heterogeneity *within* each area depending on season and time of day.

Introduction

Indo-Pacific humpback dolphins (*Sousa chinensis*) inhabit the coastal waters from Myanmar to central China and the Indo-Malay Archipelago (Jefferson & Smith, 2016: Würsig et al., 2018). Their preference for shallow waters near estuaries and river mouths places them close to large concentrations of humans, making them particularly susceptible to anthropogenic activities. As a result, many populations are now in decline (Jefferson and Smith, 2016; Würsig et al., 2018). Humpback dolphins that use the waters of Hong Kong are part of the Pearl River Estuary (PRE) population, the largest and most well-studied population of Indo-Pacific humpback dolphins (Chen et al., 2010; Jefferson & Hung, 2004). This population itself is part of the nominotypical subspecies, *Sousa chinensis chinensis*, of humpback dolphins (Wang et al., 2016). The PRE consists of the waters of Macau, Hong Kong and the People's Republic of China (**Fig. 1**) (Jefferson & Hung, 2004).

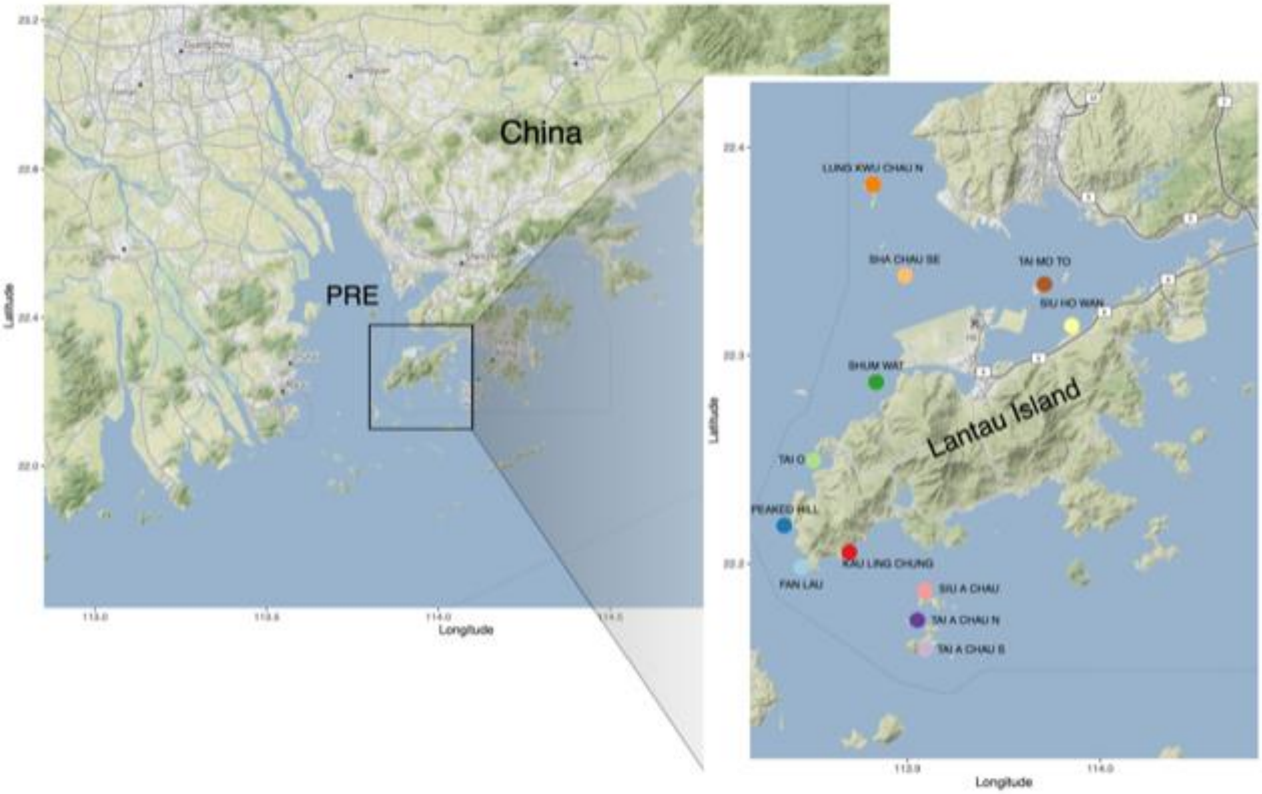

Figure 1: Maps showing study area. PRE stands for Pearl River Estuary. C-POD locations are shown by coloured dots on the inset map. Dotted line around Lantau Island represents Hong Kong boundary. Maps made with ggmap function in R (Kahle & Wickham, 2013).

There is evidence that dolphin abundance in Hong Kong waters has dramatically declined since the late 1990’s from around 200 individuals to 32 individuals in 2019 (Hung, 2019; Jefferson et al., 2009; Würsig et al., 2016). Hong Kong remains one of the busiest ports in the world, threatening the dolphin population with habitat loss due to land reclamation, habitat degradation due to chemical and acoustic pollution, and anthropogenic injuries and/or mortalities from transport and construction vessel traffic as well as fisheries activities (Jefferson & Hung, 2004; Jefferson et al., 2009; Munger et al., 2016; Würsig et al., 2016). Large development projects such as expansion of the Hong Kong International Airport (HKIA) and construction of the Hong Kong-Zhuhai-Macau Bridge (HKZMB) have increased vessel traffic even more, as well as both chemical and noise pollution (Munger et al., 2016; Pine, et al., 2017; Piwetz et al., 2012; Sims et al., 2012). In addition to this decline, the ways in which the dolphins use the area has also changed. Historically, dolphins were sighted frequently throughout the waters surrounding Lantau Island (Jefferson, 2018; Jefferson & Hung, 2004), but recently in 2018-2019 they have been sighted most frequently around the southwestern portion of the island, and to a lesser extent in the north and the south (Hung, 2019).

Humpback dolphins in Hong Kong waters have been extensively studied by both vessel and theodolite surveys since the mid 1990's (Hung, 2017, 2018, 2019; Piwetz et al., 2012; Würsig et al., 2016). Although extremely useful and informative, these data are limited to the small proportion of the animals' lives when they are visible above the water surface, such as during daylight hours, in good weather, and when the field teams are conducting surveys in an area (Tregenza et al., 2016.). Due to this limited coverage (despite extensive effort), Passive Acoustic Monitoring (PAM) offers a powerful opportunity to fill these gaps in our knowledge and compliment these observational data (Akamatsu, et al., 2001; Heenehan et al., 2017; Jaramillo-Legorreta et al., 2017; Tregenza et al., 2016; Zimmer, 2011).

Cetacean Porpoise Detectors (C-PODs) produced by Chelonia Ltd. (Cornwall, UK) are a small autonomous PAM device that log acoustic activity in the form of echolocation signals (Tregenza et al., 2016, Chelonia Ltd., 2018). They have the ability to detect all odontocetes other than sperm whales (*Physeter macrocephalus*), which have echolocation clicks at frequencies outside of the detection range of the C-PODs (Chelonia Ltd., 2018). C-PODs are unaffected by light and weather conditions and can log continuously for several months at a time (Chelonia Ltd., 2018). Although digitised sounds are not stored, C-PODs record the time of occurrence, centre frequency, intensity, duration, bandwidth and frequency of tonal clicks within the detectible frequency range (Chelonia Ltd., 2018). Due to this ability to continually detect animals in many situations when visual detections are not possible, C-PODs have provided a wealth of information on the distributions, habitat use patterns, and echolocation activities for a number of species (Clay et al., 2018; Gallus et al., 2012; Heenehan et al., 2017; Jaramillo-Legorreta et al., 2017; Leeney et al., 2011; Rayment et al., 2010, 2011; Todd et al., 2009; Verfu et al., 2006).

Past deployments have shown that C-PODs are a reliable and successful PAM system to detect the presence of humpback dolphins (and Indo-Pacific finless porpoises, *Neophocaena phocaenoides*) in Hong Kong (Hung & Wang, 2018). In this study I used C-POD data collected over a year to assess the diel, seasonal, and geographic patterns of acoustic activity of Indo-Pacific humpback dolphins in Hong Kong waters. Given the concern over the future of humpback dolphins in Hong Kong waters—with the degree of human development, the recent decline in dolphin numbers, and their shift in habitat use patterns—the goal of these analyses is to use these acoustic data to enhance our understanding of dolphin habitat use at a finer spatial and temporal scale than is available based solely on visual surveys. This level of resolution will be important for identifying where and when conservation efforts could most effectively be distributed to better protect the dolphins and improve their chances of survival into the future.

Materials and Methods

Data collection

A C-POD consists of a polypropylene casing with a hydrophone housing at one end, a 4 GB secure digital (SD) card, a silica gel pack (prevents condensation), 10 alkaline D-cell batteries and a removable lid (Chelonia Ltd., 2018). Maximum deployment times vary depending on the environment (activity, noise) and capacity of the D-cell batteries and SD Cards (Chelonia Ltd., 2018). From June 25th, 2018 to July 5th 2019, twelve C-PODs were deployed in Hong Kong waters around Lantau Island, as part of an ongoing PAM study conducted by the Hong Kong Cetacean Research Project (HKCRP) and primarily funded by the Agriculture, Fisheries and Conservation Department (AFCD) (**Fig. 1**). Two C-PODs were deployed in both the Sha Chau and Lung Kwu Chau Marine Park (SCLKCMP) and Brothers Marine Park (BMP), three each in two planned marine marks: Southwest Lantau Marine Park (SWLMP) and South Lantau Marine Park (SLMP) and one in Shum Wat and one in Tai O, which previous line-transect studies have shown to be high dolphin density areas. The C-PODs were fixed horizontally to a metal frame (**Fig. 2**) (80cm x 80cm) which sits on the sea floor and were deployed and retrieved by professional divers every two to four months throughout the year.

Figure 2: Photo of metal frame (80cm x 80cm) in which C-POD is fixed horizontally.

Data processing

C-POD files were first analyzed using the instrument-specific software: CPOD.exe version 2.044 (Chelonia Ltd, UK). The data were processed through two automated classifiers within the software, KERNO and GENENC. The first classifier, KERNO, filters for clicks that belong to a train (containing at least five clicks), and classifies the clicks into four different types: Narrow Band High Frequency (NBHF, porpoise), other cetacean (dolphin), sonar, Weak Unknown Train Source (WUTS); as well as into three different quality classes: high, moderate and low. The second classifier, GENENC, filters for click trains that specifically belong to dolphins ("other cet").

To assess the potential for false positives, 100 randomly sampled minutes from each processed file underwent visual validation to determine if a true dolphin click train was present. In the advanced train filters section, mean Source Pressure Level (SPL) was set to 50 for all files to help remove noise, and thus the number of false positive detections in the file. All click trains belonging to "Other cet" under the KERNO and GENENC classifiers in all three quality classes were exported in Detection Positive Minutes (DPMs) per hour and per day for each file for the entire time the devices were logging.

Statistical analyses

To better understand the relationships among dolphin detections, locations, time of year and time of day, I built a series of regression models starting with just one predictor variable at a time (location, time of year, time of day), then considered all predictor variables together, then considered the addition of pairwise interactions, and lastly with the addition of the single three-way interaction (locations x time of year x time of day),

Including each month and hour would make these models untenable, for example the three-way interaction on its own would have 3,456 (12 locations x 12 months x 24 hours) effect parameters to be estimated. I was also concerned that dividing the data so finely would result in many scenarios or combinations with very few data points. Lastly, I was also interested in identifying general patterns rather than fine-scale details that could instead be the focus of future studies. Therefore, I collapsed month in to “Dry Season” (December to May) and “Wet Season” (June to November), and hour into “Day” (7:00 – 19:00) and “Night” (19:00 – 7:00).

Although the raw data and Figures 2-4 are based on detection positive minutes (DPM), I was concerned that there would be strong autocorrelation in these data (*i.e.*, if dolphins are detected in one minute, it is more likely that the adjacent minutes will also have a detection). Therefore, for statistical analyses I changed the scale to detections positive hours (DPH) because I did not think dolphin detections would be autocorrelated at the hour scale. Using DPH or a greater time scale has been suggested to represent relative dolphin presenceby reducing underestimation found in shorter time scales(Garrod et al., 2018). For these models, I converted DPH to 1’s and 0’s indicating whether or not each hour had a detection, respectively. This detection record was then used as the predicted variable in binomial regression models where locations, season, and day/night were used as categorial predictor variables. I then analysed a series of models of increasing complexity to assess the effects of each predictor variable and how they changed within the context of other variables (**Table 1**). Information criteria (AIC) were used to assess how the predicting performance of the models changed as different parameters were considered. I used the glm function in R and used the argument family = binomial (link = “logit”) as our predicted variable was binomial (R Core Team, 2019). To convert values back to the original scale, I used the invlogit function from the arm package in R (v1.11-1; Gelman & Su, 2020).

Table 1: Models increasing in complexity with predictor variable(s) and AIC values

Model	**Predictor Variable(s)**	**AIC Value**
Model 1	Location	71160.62
Model 2	Season	74347.98
Model 3	Day/night	74349.11
Model 4	Location + season + day/night	71159.49
Model 5	Location + season + day/night + location x season + location x day/night + season x day/night	71014.41
Model 6	Location + season + day/night + location x season + location x day/night + season x day/night + location x season x day/night	71008.62

Results

Data characteristics

From June 25, 2018 to July 5, 2019 approximately 1.7% of minutes-by-locations surveyed had detections (103,846 detection positive minutes out of 6,274,620 acoustically surveyed minutes). There were substantial differences in the total DPM by C-POD location (**Fig. 3**). Peaked Hill had the highest number of total DPMs (34,739) while Tai Mo To had the least (168). There was also substantial heterogeneity in DPM during different months of the year (**Fig. 4**), as well as during different hours of the day (**Fig. 5**). For example, Peaked Hill had a higher proportion of DPMs in the summer months than in the winter months (**Fig. 4**) and Shum Wat had a higher proportion of DPMs at night than during the day (**Fig. 5**).

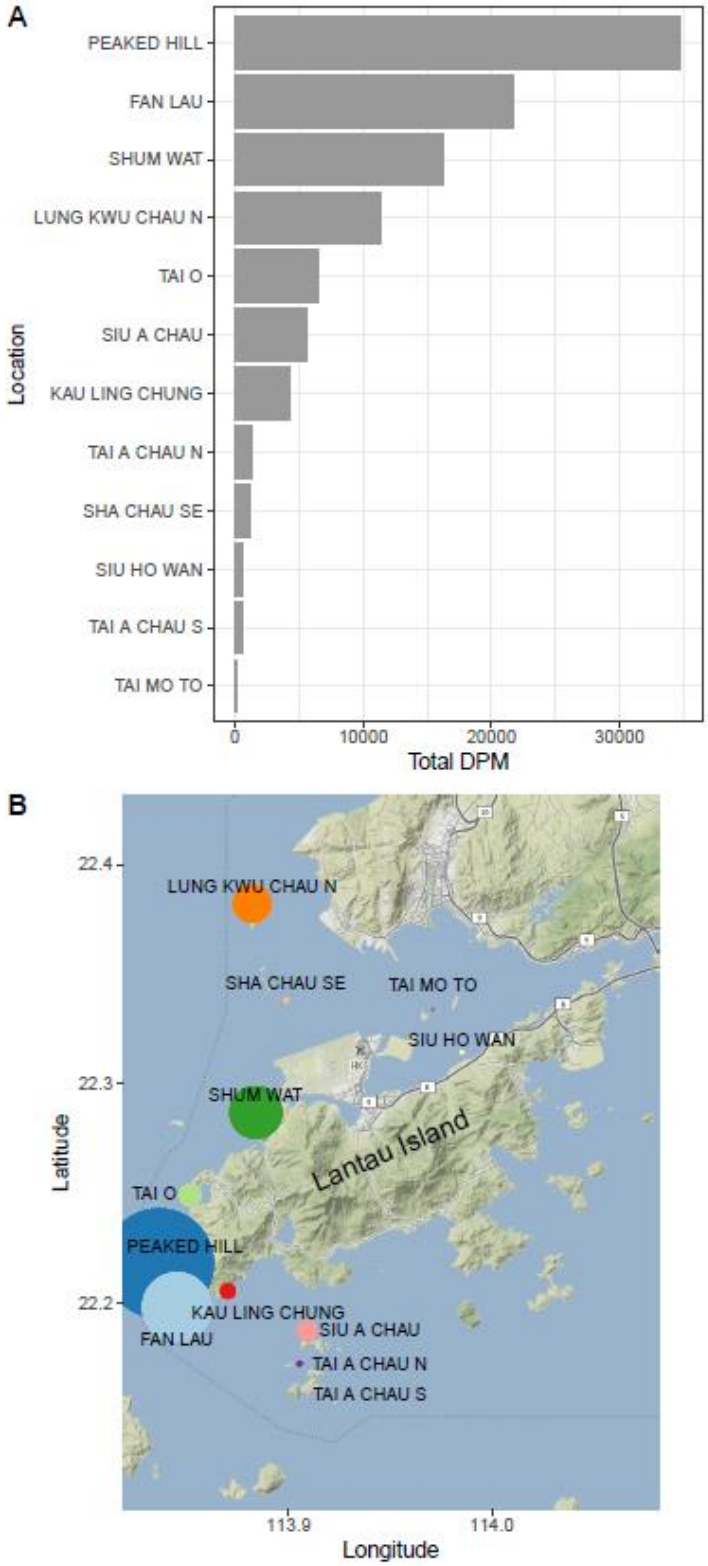

Figure 3: Total number of Detection Positive Minutes (DPM) by C-POD location, represented - (A) as a bar graph going from highest to lowest and (B) as a map, with location circles coloured as in Fig. 1, and size of the circles indicating relative number of detections.

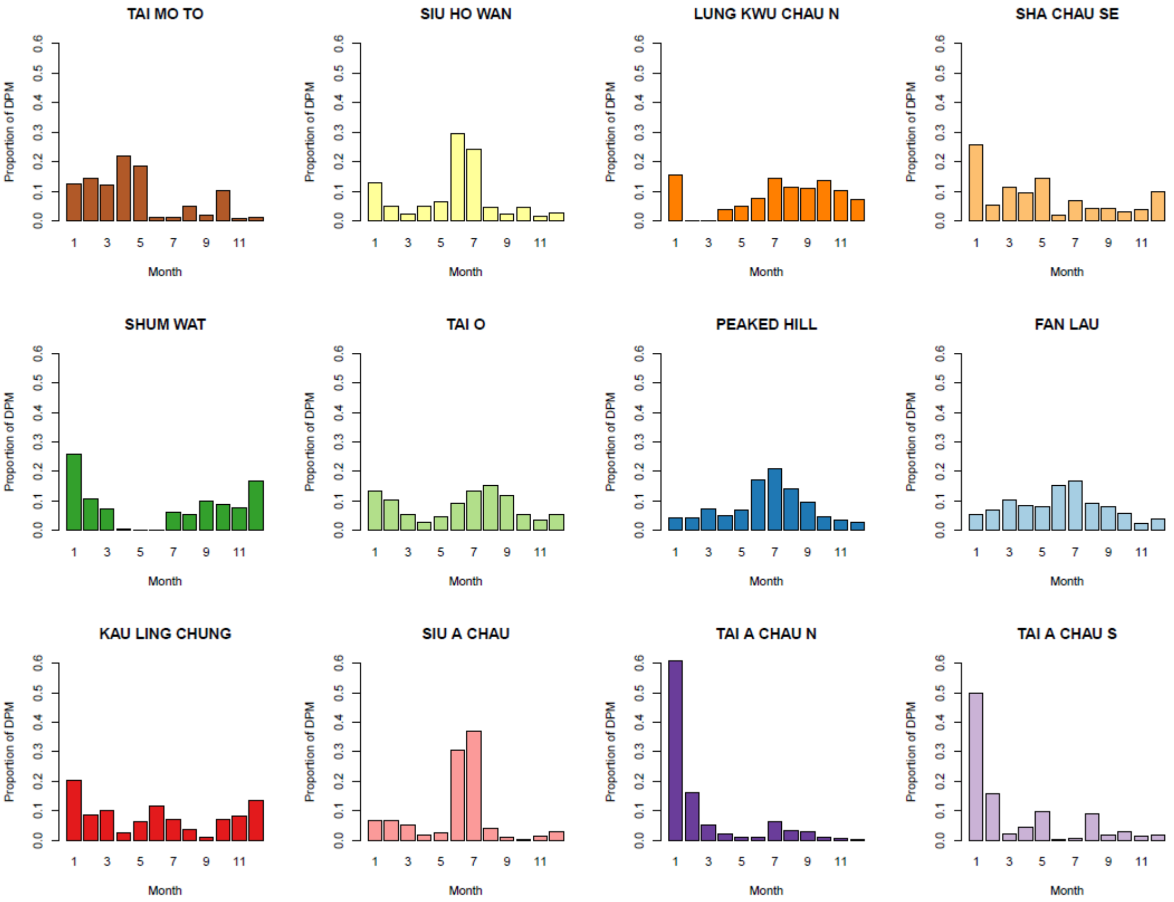

Figure 4: Proportion of Detection Positive Minutes per Month of the year within each location (*i.e.*, the number of DPMs within each month at each location divided by the total number of DPMs for that location). Colours correspond to those used for the Map in **Fig. 1**. Locations are plotted starting at the Tai Mo To in the northeast and then moving counter-clockwise around Lantau Island.

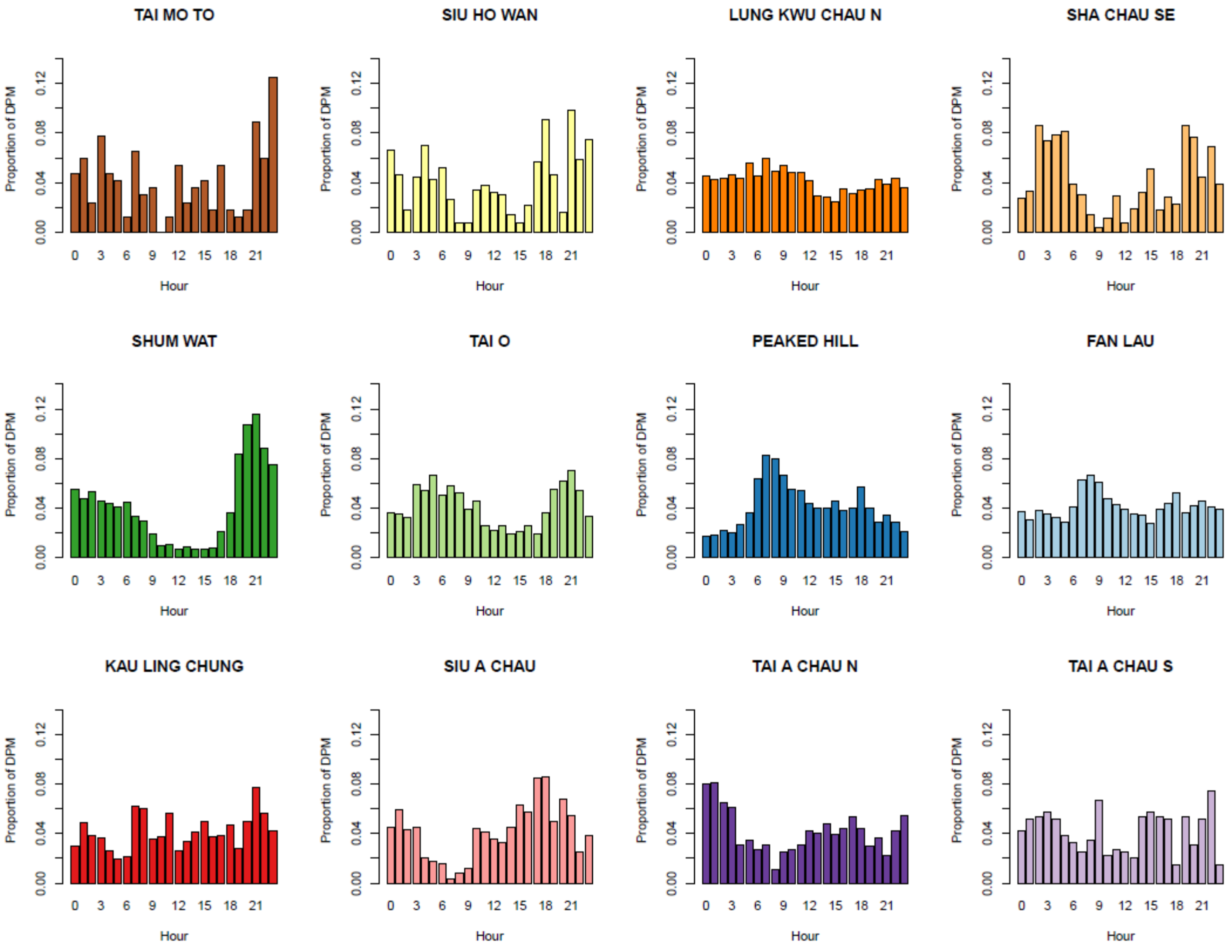

Figure 5: Proportion of Detection Positive Minutes per hour of the day within each location (*i.e.*, the number of DPMs within each hour at each location divided by the total number of DPMs for that location). Colours correspond to those used for the Map in **Fig. 1**. Locations are plotted starting at the Tai Mo To in the northeast and then moving counter-clockwise around Lantau Island.

Model Results

When each predictor variable was considered independently, location showed a clear and statistically significant effect on the probability of detection (**Fig. 6**, p<0.001). Season and day/night did not exhibit statistically significant effects when considered independently (**Figs. 7** and **8**). However, the wide variation of the estimated effects, combined with the plots from the raw data, suggested that these variables had location-specific effects that would only be detected when including interaction effects. This was indeed the case, where the model including all pairwise interactions (model 5) indicated that all pairwise interactions had significant effects. Comparison of all models showed that the full model (model 6, which include all individual effects, pairwise interactions, and the three-way interaction) had the lowest AIC value, although it was only slightly lower than that of model 5 (**Table 1**). A plot of these effects by location is shown in **Fig. 8**.

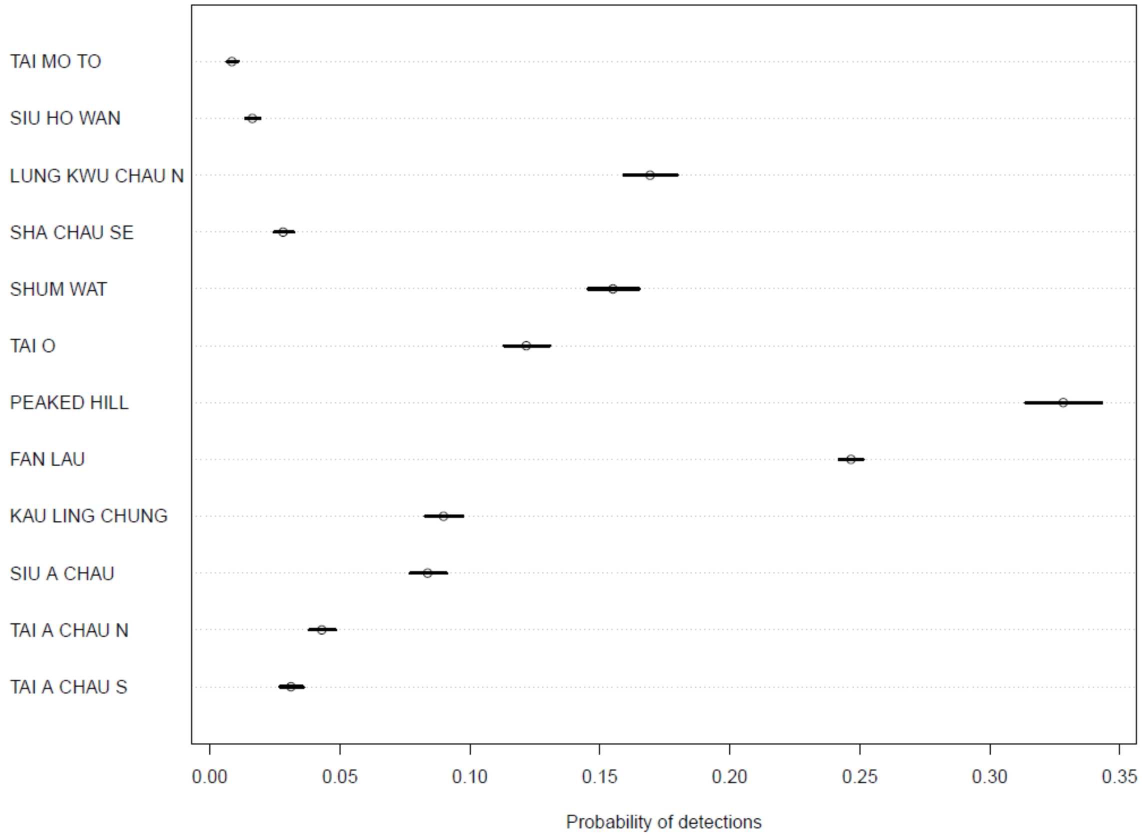

Figure 6: Relative effect of location on probability of detection based on model 1 where location was the only predictor variable. Circles represent the mean effect and bars indicate 2σ (2 standard deviations) from the mean.

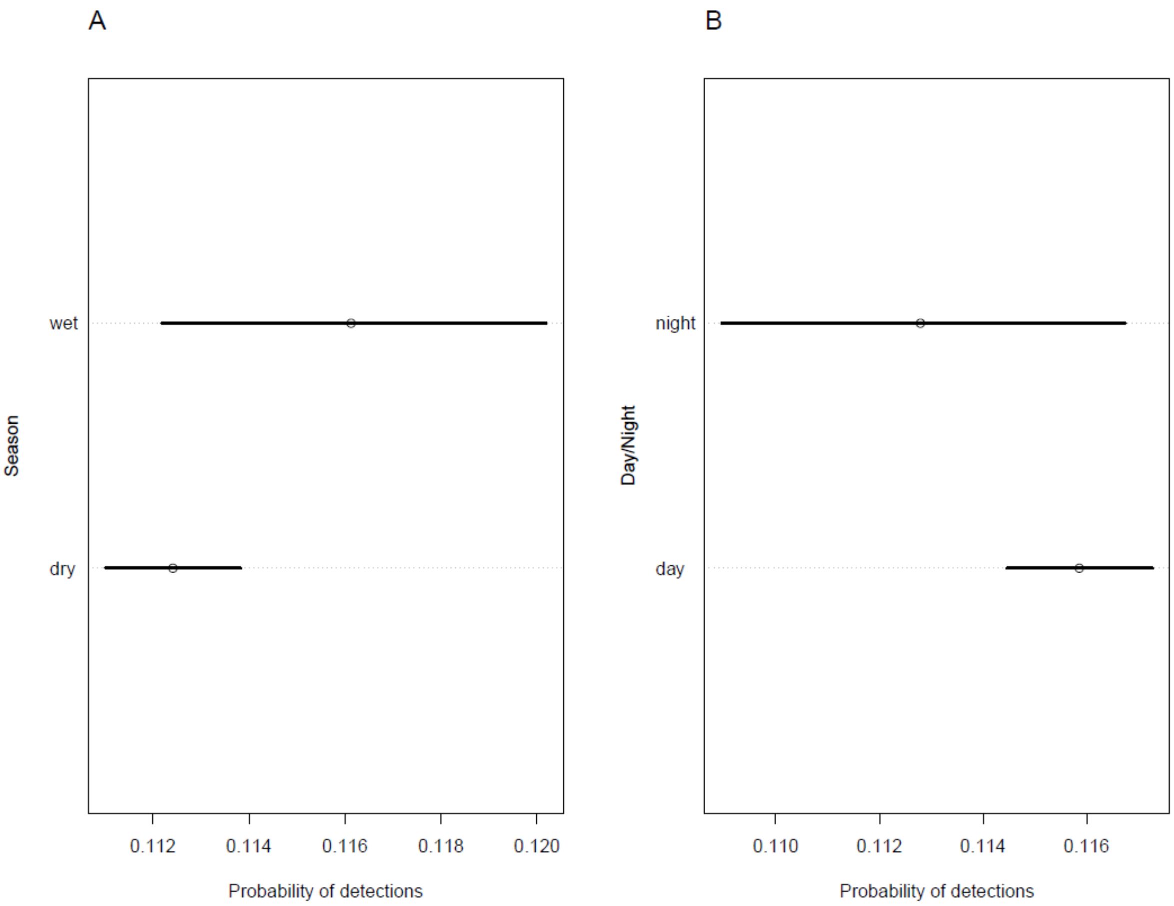

Figure 7: (A) Relative effect of season on probability of detections based on model 2 where season is the only predictor variable. (B) Relative effect of time of day on probability of detection when day/night is the only predictor variable (model 3). Circles represent the mean effect and bars indicate 2σ (2 standard deviations) from the mean.

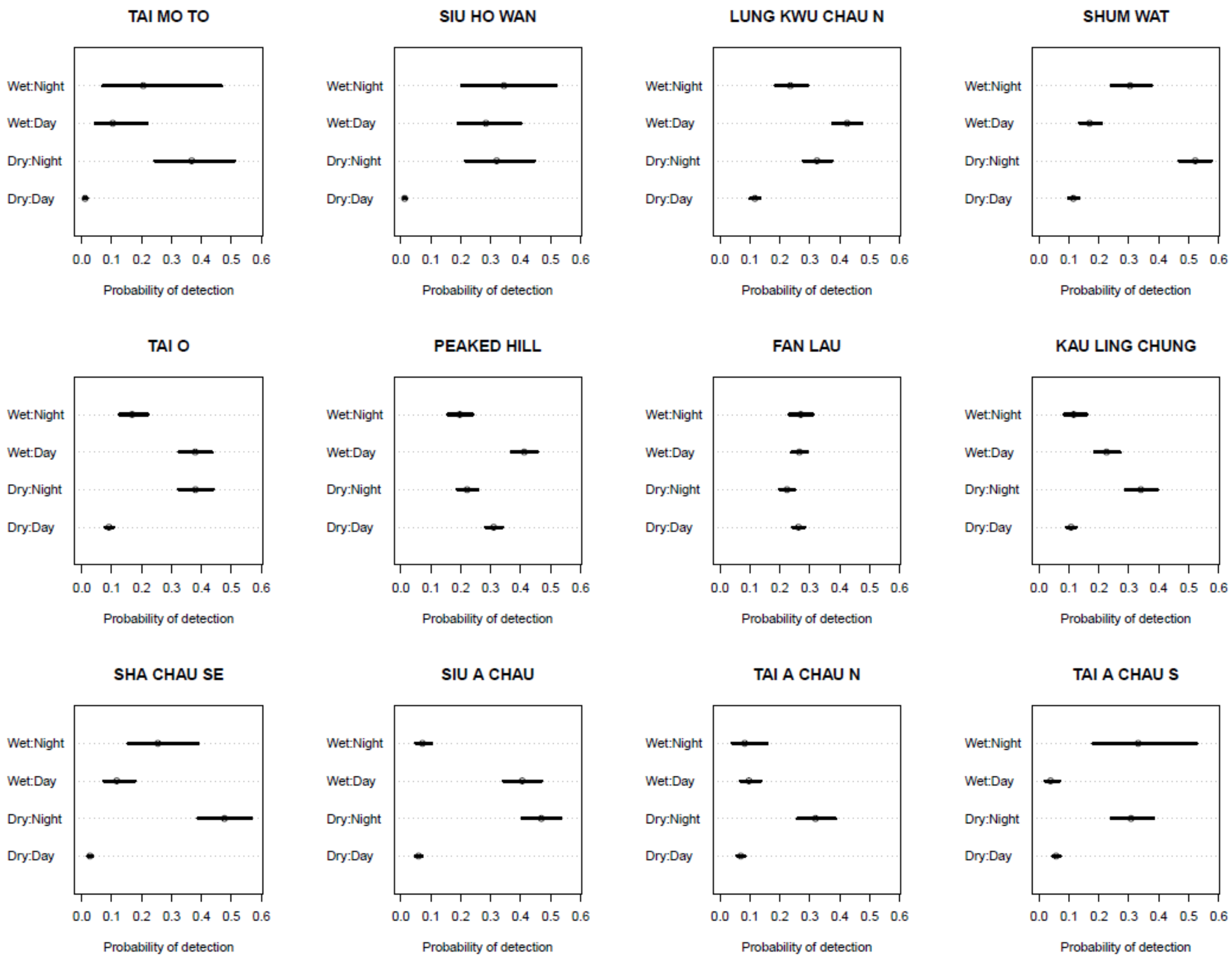

Figure 8: Effects of season and day/night on the probability of detection within each location, as estimated from model 6, which includes all individual effects, all pairwise interactions, and the single three-way interaction of location x season x day/night.

Discussion

The main finding of this study is that location, time of year, and time of day all have substantial effects on the probability of detection of humpback dolphins in Hong Kong waters, with location having the largest effect. For the most part, the acoustic data complemented what has been learned from the visual surveys. Out of the twelve locations, Peaked Hill had the greatest number of detections. Peaked Hill was followed by Fan Lau, Lung Kwu Chau N, Shum

Wat and Tai O. These five locations are all located off the west coast of Lantau Island with four of the locations (other than Lung Kwu Chau N) concentrated around southwestern Lantau (**Fig. 1**). This coincides well with the sighting data, where dolphins have most frequently been sighted along the west coast and mainly between Tai O and Fan Lau (Hung, 2019).

The effect of season on the probability of detections differed substantially across locations and time of day (**Fig. 8**). However, since these data only represented a single year, each season is only represented once, and therefore these effects should be taken as preliminary because there could be heterogeneity in seasonal effects in different years. For many locations (Siu Ho Wan, Lung Kwu Chau N, Tai O, Peaked Hill, Fan Lau, Kau Ling Chung, Siu A Chau) the acoustic data showed that the highest number of detections in these locations occurred during the wet season months (**Fig. 4**). The estuarine hydrography of the Pearl River Estuary off the western waters of Hong Kong is complex (Hung & Jefferson, 2004). Temperature, salinity, visibility and rainfall amounts vary with the time of year. Although various hydrological parameters likely affect dolphin occurrence in Hong Kong, prey availability is suggested to be the most important factor impacting dolphin distribution within the PRE (Hung, 2008; Pine et al., 2016).

The effect of diel pattern (day or night) on the probability of detections also differed significantly across locations and across season within each location (**Fig 7B**). Some locations, such as Sha Cha SE, Shum Wat, Tai O and Siu A Chau, displayed clear diurnal patterns; whereas other locations (such as Lung Kwu Chau N and Tai A Chau S) showed relatively uniform detection probabilities across times of day. Other PAM studies in Hong Kong and the PRE both reported significantly larger numbers of detections at night than during the day, but they also used different ways to classify day and night (Munger et al., 2016; Wang et al., 2015). Whereas I collapsed hour into “Day” (7:00 – 19:00) and “Night” (19:00 – 7:00). The Munger et al. (2016) study used ecological acoustic recorders (EARs) and day and night were categorized with approximate sunrise to sunset hours of 06:00-18:00 for spring (March-May) and autumn (September-November), 06:00-19:00 in the summer (June-August) and 07:00-18:00 in the winter (December-February). Munger et al. (2016) also found that diel patterns varied greatly among sites. Wang et al. (2015) used Acoustic data loggers (A-tags) and diel phases were divided into night1, morning, day, evening and night2 based on civil twilight equations.

By Region and/or Marine Park

Northeast Lantau

Northeast Lantau has historically been an area where humpback dolphins were frequently sighted (Hung, 2019). However, several large development projects have taken place there, including the construction of the third runway of the Hong Kong International Airport (HKIA) and the Hong Kong Zhuhai Macau Bridge (HKZMB) and an increase in high-speed ferry traffic to and from the Sky Pier. Integrated into the HKIA, the Sky Pier is cross-boundary ferry service which performs over a hundred trips a day through dolphin habitat. The Brothers Marine Park (BMP) was established in 2016 to aid the recovery of dolphins to the area (which includes the Tai Mo To and Siu Ho Wan C-POD sites). Dolphin sightings dramatically declined in Northeast Lantau since 2012 and have shown no signs of recovery after the HKZMB was completed in 2017. Disturbance from the massive 3RS project for the third runway of the HKIA involving approximately 650 hectares of land reclamation north of HKIA since 2016 may also potentially be affecting the recovery of dolphins in the area. Similar to the visual data, these two sites had very few acoustic detections. However, despite this low number, there were still acoustic detections throughout the year in both locations (**Fig. 4**), indicating that dolphins have not completely abandoned the area. These acoustic detections are particularly important because there has been an almost total absence of visual detections of dolphins in this area over the past five years, other than a few rare sightings near Tai Mo To in December 2017 and near Siu Ho Wan in February 2018 (Hung, 2019). Therefore, the acoustic data indicated occasional, yet greatly reduced, use of this area during a time period whereas visual surveys suggested an almost complete absence of dolphins.

Northern Lantau

Dolphin occurrence in Northern Lantau (including two C-POD sites: Lung Kwu Chau N and Sha Chau SE, **Figs. 1,3**) has been greatly reduced over the last several years, with most sightings concentrated around Lung Kwu Chau N, which—based on sighting data—remains the only area in Northern Lantau consistently used by dolphins (Hung, 2019). The acoustic data show a similar pattern with Lung Kwu Chau N having the fourth largest number of detections overall while the other northern location (Sha Chau SE) has the fourth lowest number of detections. These two locations are located within the Sha Chau and Lung Kwu Chau Marine Park (SCLKCMP) which was designed in 1996 as an important habitat for humpback dolphins. Dolphins were detected throughout the year in both locations, although Lung Kwu Chau N had a very low number of detections in February and January (**Fig. 4**). Lung Kwu Chau N had a consistent number of detections throughout the hours of the day while Sha Chau SE had peaks in detections in the early morning and evening hours (**Fig. 5**). Würsig and Piwetz (2014) reported that dolphins tended to use Sha Cha in the late morning and again in the afternoon and were off Lung Kwu Chau from late morning through early afternoon based on their theodolite study.

Western Lantau

Shum Wat and Tai O are located along western Lantau and have been known to be important high density and travelling areas for dolphins. This area also recorded a steady decline after reaching the highest dolphin densities in 2009 and the lowest in 2017 and 2018 (Hung, 2019). Shum Wat had higher number of detections during the night in the dry season than other times while Tai O had a higher number of detections during the day in the wet season and in the night during dry season, lower values during the night in the wet season. Specifically, Shum Wat had a very low number of detections from April to June and the highest number of detections in December and January and detections, whereas Tai O peaked in the August (**Fig. 4**). Throughout the hours of the day, Shum Wat displayed the clearest pattern of detections of all the locations with highest number of detections at night and detections decreasing during the day (**Fig. 5**). Tai O also showed a similar pattern in detections with the highest number of detections in the early morning hours and the evening (**Fig. 5**).

Southwest Lantau

Peaked Hill, Fan Lau and Kau Ling Chung are all located within the proposed Southwest Lantau Marine Park (SWLMP). Dolphin occurrence around southwestern Lantau has shown a large increase over the past several years, reaching the highest number in 2018 but declining since then (Hung, 2019). Evidence of changes in individual habitat use has also been noted in recent years with some individuals exhibiting range expansions or shifts from western Lantau to southwest Lantau waters (Hung, 2019). Peaked Hill and Fan Lau were the areas with the highest number of acoustic detections (**Fig. 3**), and these also represent the areas where dolphins are most frequently sighted (Hung, 2019). In Fan Lau and Peaked Hill, dolphins were detected regularly regardless of season and time of day, especially in Fan Lau which showed a similar probability of detections across all conditions (**Fig. 8**). Generally, in southwest Lantau, dolphin sightings declined from December to March, reaching the lowest numbers in April and May and increasing again in June (Hung, 2008). These are somewhat similar to the patterns in the acoustic data, which also show the largest numbers of detections in June-July, at least for Peaked Hill and Fan Lau (**Fig. 4**). All three locations displayed a similar pattern of detections for hours of the day with detections peaking in the early morning hours (~6h00-9h00) with another peak in detections in the evening (**Fig. 5**).

Southern Lantau

The region of “southern Lantau” encompassed three C-POD sites: Siu A Chau, Tai A Chau N, and Tai A Chau S (**Figs. 1 & 3**). These three sites are located within the proposed South Lantau Marine Park (SLMP). Major vessel fairways exist in southern Lantau where significant vessel traffic occurs in addition to hundreds of daily high-speed ferry trips. After a dramatic increase in dolphin occurrence in 2014, dolphin densities have declined in this area from 2014-2018 with 2018 being the lowest since 2004 (Hung, 2019). In this more saline area of Hong Kong, there is partial habitat overlap with the Indo-Pacific finless porpoise (*Neophocaena phocaenoides*). In terms of acoustic detections, the site closest to Lantau Island (Siu A Chau) had the most detections of the three C-POD sites in the area, and the seventh highest number of detections across all sites (**Fig. 3**). The number of detections then declined at sites as they increased in distance from Lantau Island (Tai A Chau N had more detections than Tai Chau S). Tai A Chau N and Tai A Chau S both had the largest number of detections in January while Siu A Chau had the largest number of detections in June and July (**Fig. 4**). All three locations displayed a dip in detections in the early morning hours (between 6h00-9h00) with an increase in late afternoon and evening (**Fig. 5**).

Conclusion

The passive-acoustic data reported here add substantially to our understanding of habitat use by humpback dolphins in Hong Kong waters. Although general patterns are very similar between visual and acoustic data (for example, which locations have the most detections), the acoustic data reveal some patterns not possible with visual data. First, the acoustic data show that dolphins are consistently still using a once-popular area (northeast Lantau) that appeared to have largely been abandoned based on visual surveys. However, even though the acoustic detections show consistent use of this area, the number of detections were quite low, indicating much reduced use from earlier years. The acoustic data also provide information on diel patterns of habitat use, which are much harder to obtain from visual surveys. These analyses showed that season and time of day have significant impacts on acoustic detection probabilities, but that these effects differ by location. Thus, these data provide a finer-scale understanding of dolphin habitat use in Hong Kong waters, that should be used to guide the placement of research and management efforts in the future.

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CHAPTER 3

Comparison of acoustic and visual detection methods of Indo-Pacific humpback dolphins (*Sousa chinensis chinensis)* in Hong Kong waters

Abstract

The Indo-Pacific humpback dolphins that occur in Hong Kong waters (*Sousa chinensis chinensis*) face numerous anthropogenic threats and their numbers have dramatically declined since the late 1990's. Extensive visual surveys have been carried out in these waters since 1995; however, to supplement these visual data and to provide information to aid the conservation of humpback dolphins, twelve C-PODs were deployed throughout their habitat from June 2018-July 2019. Here, I compared these visual and acoustic data to: (a) characterize the ability of C-PODS to detect humpback dolphins in these waters, and (b) assess the relative efficacy of each detection method. There were 653 occasions where the vessel surveyed within 1000m of a C-POD, 93 of which dolphins were detected by one or both methods. On eight occasions (~8.6%) dolphins were detected both visually and acoustically, on 76 occasions (~81.7%) dolphins were detected visually but not acoustically and on nine occasions (~9.7%) dolphins were detected acoustically but not visually. The lack of overlap in acoustic and visual detections was surprising, suggesting that the C-PODs may frequently miss dolphins. Likely causes of these missed detections are the directionality of dolphin echolocation clicks, and perhaps aspects of the environment (vessel traffic and acoustic disturbance due to the shallow water). Given the low amount of detections made both acoustically and visually, it was not possible to estimate a detection curve for the C-PODs. Group size was slightly larger in cases when dolphins were detected both acoustically and visually than in cases when dolphins were detected just visually. Despite these limitations, the ability of the C-PODs to survey continually represents a valuable addition to population monitoring efforts.

Introduction

Indo-Pacific humpback dolphins (*Sousa chinensis chinensis*) that occur in Hong Kong waters are part of a larger population that inhabits the Pearl River Estuary (PRE) (**Fig. 1**) (Jefferson, 2018). Hong Kong is one of the world's busiest ports and areas of rapid coastal development where humpback dolphins face high levels of habitat degradation, pollution (chemical and noise), and high levels of vessel traffic and fishing activities (Jefferson et al., 2009). The numbers of dolphins using Hong Kong waters have decreased over the years, dropping from around 200 individuals in the late 1990s to an estimate of about 32 individuals in 2018-2019 (Hung, 2019). To better understand the status of this population and the effect of anthropogenic threats, intensive visual surveys have been conducted since 1995.

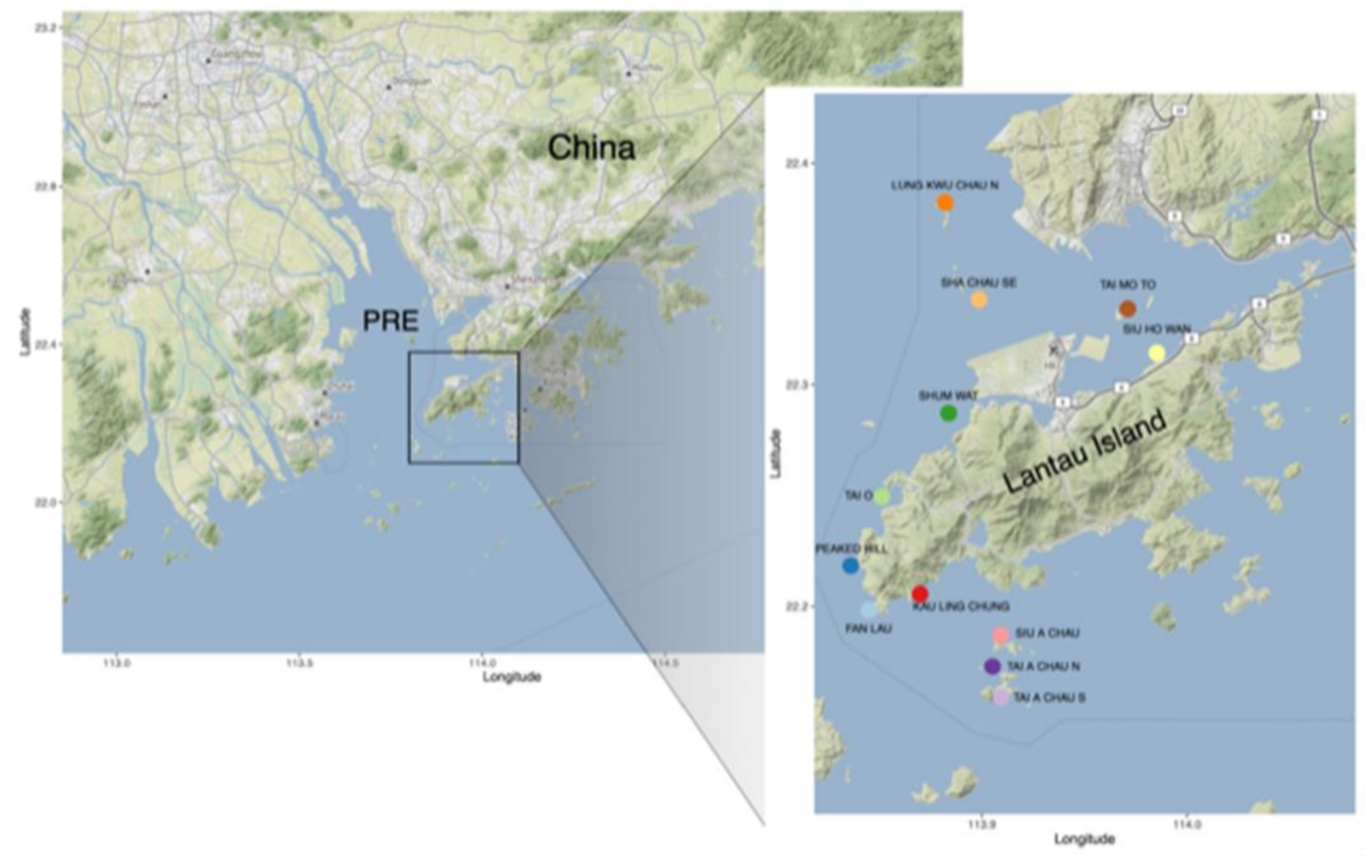

Figure 1: Maps showing study area. PRE stands for Pearl River Estuary. C-POD locations are shown by coloured dots on the inset map. Dotted line around Lantau Island represents Hong Kong boundary. Maps made with ggmap function in R (Kahle & Wickham, 2013).

Since 1995, the Hong Kong Cetacean Research Group (HKCRP) have conducted a long-term monitoring study of humpback dolphins and Indo-Pacific finless porpoises (*Neophocaena phocaenoides*) in Hong Kong waters. The main focus of their work includes collecting data for assessing the distribution and abundance of both species in addition to taking photographic records of individuals to better understand various aspects of the population, such as estimating population size, monitoring trends in abundance, distribution, habitat use, behaviour and mortality rates.

The HKCRP conducts line-transect surveys in ten areas around Hong Kong (**Fig. 2**). During a one-year period (April 2018 – March 2019), 192 line-transect vessel surveys with 6,055.6 km of survey effort were conducted (Hung, 2019). When dolphins are sighted, the team will go off-effort and approach the animals to photograph for their photo-identification and mark-recapture work. Despite this effort, visual surveys can only take place during the day and in good weather and the team can only be in one place at a time. Therefore, to broaden the coverage of their surveys, the HKCRP has begun supplementing their visual surveys with passive acoustic monitoring.

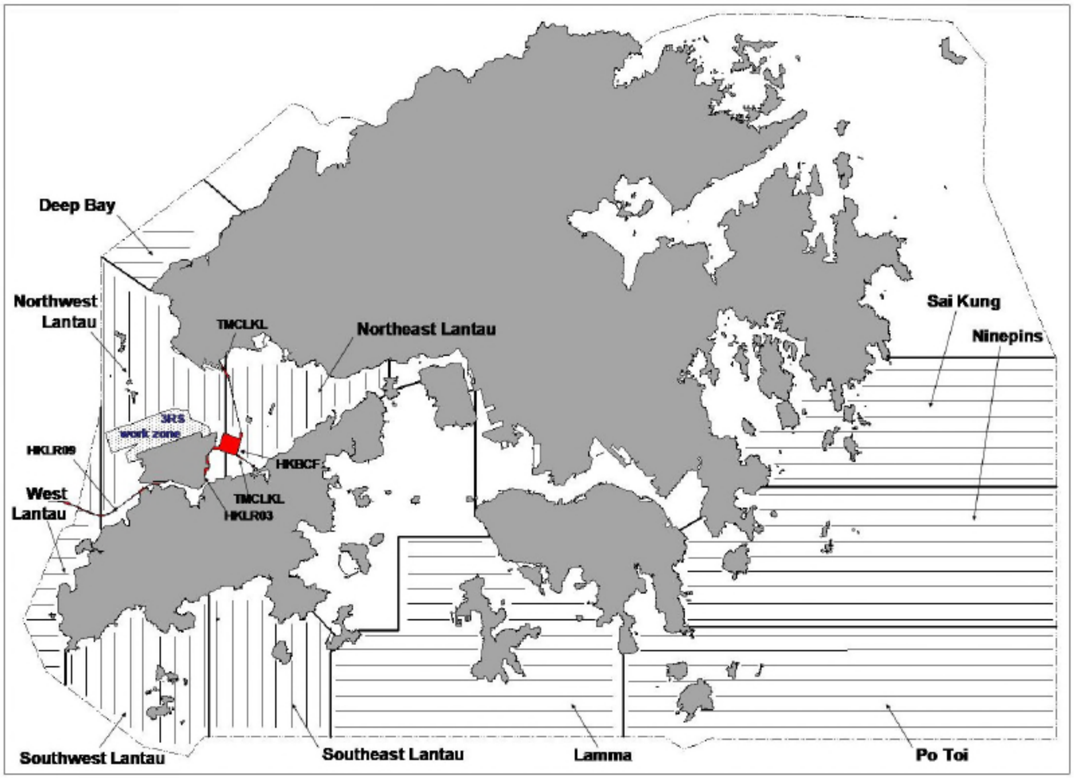

Figure 2: Survey areas with transect lines conducted by HKCRP. We only looked at those conducted in Northeast Lantau, Northwest Lantau, West Lantau and Southwest Lantau where humpback dolphins are primarily found.

Passive Acoustic Monitoring (PAM) involves placing acoustic detection equipment in the environment to continually survey and record acoustic data, and has proven to be a useful way to detect cetaceans and improve our understanding of many aspects of their biology and distribution (Zimmer, 2011). PAM devices allow researchers to study cetaceans continuously for extended periods of time and are unaffected by light and weather conditions and thus provide valuable data on temporal and spatial habitat usage. Previous PAM research on humpback dolphins around northern Lantau Island on either side of the Hong Kong International Airport (HKIA) showed the greatest detection rates on the northwestern side of the HKIA (Munger et al., 2016). Detection rates were also greater from June to November with lower rates from March to May (Munger et al., 2016). Lastly, detection rates were higher at night than during the daylight hours

(Munger et al., 2016). Fish abundance seemed to have a greater influence on dolphin distribution within the Pearl River Estuary compared with vessel activity (Pine et al., 2017).

Cetacean Porpoise Detectors (C-PODs) are small autonomous PAM devices that log echolocation signals in the form of "click trains". C-PODs are able to detect odontocetes with echolocation click trains (five or more clicks) that fall within the frequency range of 20-160kHz. The use of C-PODs has provided information on habitat use patterns, echolocation behaviour, and on the effects of construction noise and long-term monitoring of many odontocete species (Heenehan et al., 2017; Jaramillo-Legorreta et al., 2017; Leeney et al., 2011; Rayment et al., 2010, 2011). Differing from other PAM devices, C-PODs do not store audible sounds but instead create a 'timestamp' for each click based on their waveform characterisation of frequency, duration, bandwidth and intensity (Nuuttila et al., 2018). Instrument-specific software then classifies the clicks into four categories based on their characteristics (dolphin, porpoise, sonar, weak unknown train sources) and provides a quality class (high, moderate, low, doubtful). Humpback dolphin click spectrums extend from around 30 kHz to around 200 kHz, and therefore they fall within the detection frequency range of C-PODs (Goold & Jefferson, 2004; Wang & Hung, 2018).

One key aspect of using C-PODs for population monitoring is understanding at what distance they can reliably detect individuals, and thus identify what area is effectively being surveyed. C-PODs are produced to have an effective detection range (EDR) of about 1000m for dolphins and 400m for porpoises. However, to date only a few studies have assessed the actual detection distance of C-PODs with dolphins in the field. As one example, Nuutilla et al. (2013b) found that the mean maximum detection distance for bottlenose dolphins (*Tursiops truncatus*) in Cardigan Bay, Wales to be 1512m with a median detection distance of 563m, confirming that the

C-PODS would be able to detect dolphins at 1000m. As another example, also with *T. truncatus,* Roberts and Read (2014) could detect dolphins in the New River Estuary, North Carolina at up to 933m from using the C-POD, with detection distances ranging from 495-809m on one device and 763-933m on another.

More data are available on the effective detection distances of C-PODs with porpoises, and harbour porpoises (*Phocoena phocoena*) in particular. Based on analysis of playbacks, Nuuttila et al. (2018) found that harbour porpoises off New Quay, Wales could be detected up to a maximum distance of 566m, with a mean detection distance of 248m (95% CI: 181-316). The detection probability falling sharply between 100 and 300m. Combined, these data largely support the claimed effective detection distances provided by Chelonia Ltd. (the manufacturer of C-PODs), with respect to both dolphins and porpoises. However, data are still limited, and the ability of C-PODs to detect cetaceans will vary by the specific characteristics of each environment in which they are used.

When both visual and acoustic data are available it can be informative to compare the two to act as checks for one another and to assess the relative efficacy of each. There are not many studies comparing acoustic and visual data with C-PODs specifically, but those that have been conducted found that, overall, C-PODs are effective in detecting dolphin presence, patterns of habitat use, and providing insight into the behavioral state of animals when compared to visual data (Campbell et al., 2017; Castellote et al., 2013; Nuuttila et al., 2018; Nuuttila et al., 2013a; Nuuttila et al., 2013b; Palmer et al., 2019; Robbins et al., 2016; Williamson et al., 2016). For example, Nuuttila et al. (2013b) estimated the average probability of acoustic detection for minutes with sightings to be 0.59 (95% CI: 0.45-0.73) for bottlenose dolphins in Cardigan Bay, Wales. Group size and behavioural state also impacted detectability with a higher number of detections for animals feeding compared to travelling, and the detection probability for single dolphins was higher than for groups (Nuuttila et al., 2013b).

Similarly, comparisons of visual and acoustic data for harbour porpoises have also shown that C-POD data can be a reliable indicator of harbour porpoise presence and aid in estimating their abundance and determining the behavioural state of the animals (Jacobson et al, 2017; Nuuttila, et al., 2013a; Nuuttila et al., 2013b; Williamson et al., 2016). For example, Williamson et al. (2016) found that C-POD detections were a reliable indicator of relative density of harbour porpoises in Moray Firth, Scotland when compared to visual and digital video surveys. Additionally, Nuuttila et al., (2013a) found that foraging activity could be identified in the click trains because foraging click trains had shorter inter-click intervals and a shorter duration than those associated with other activities. C-PODs have also been an important component in the long-term monitoring of the critically endangered vaquita, *Phocoena sinus*, in the northern Gulf of California with declines in acoustic detection rates coinciding with declines in visual sightings (Jaramillo-Legorreta et al., 2017; Taylor et al., 2017). For this species in particular, C-PODs have become incredibly helpful: due to the rarity of the species and the difficulties associated with sighting individuals, the acoustic data have provided a key component to species monitoring and assessment.

Compared to other PAM devices, C-PODs have been found to perform well overall but are more conservative compared to other PAM devices (Garrod et al., 2018; Roberts & Read, 2015). For example, when C-POD performance was compared to archival acoustic recorders in the Northwest Atlantic Ocean for detecting *T. truncatus*, C-PODs were found to have a mean 99.6% positive hourly detection accuracy and mean 0.003% false positive rate (Garrod et al., 2018). PAM devices were found to detect more clicks than C-PODs, sometimes leading to a poor correlation between detections and C-PODs and other PAM devices (Sarnocinska et al., 2016). However, this is likely due to the differences between devices and software as the PAM devices used detect individual clicks compared to C-PODs which detect click trains (five or more clicks within the frequency range). Therefore, C-PODs are more likely to underestimate true dolphin occurrence by failing to detect acoustic activity that does not involve click trains, as well as by potentially missing some true click trains (Garrod et al., 2018; Roberts & Read, 2015; Sarnocinska et al., 2016).

Because of the intense and rapid anthropogenic alteration of the habitat in Hong Kong waters, and the associated rapid decline in humpback dolphins, the use of PAM devices, and C-PODs in particular, have been incorporated into survey effort to improve the resolution of survey effort. However, to provide context for how these acoustic data can be incorporated it is important to assess and characterize the performance of C-PODs in this environment. To address this issue, the first objective of this study was to combine the visual and acoustic detections to characterize the detection curve (the detection probability versus distance to the C-POD) for humpback dolphins in Hong Kong waters using C-PODS. These analyses provide important context for understanding the range, and therefore survey capabilities, of C-PODs in these waters. The second objective was to compare detections between visual and acoustic platforms to identify the relative performance of each. This includes comparing when dolphins were detected by both methods, times when dolphins were detected visually but not acoustically, and times when dolphins were detected acoustically but not visually. To do this, we used data from twelve C-PODs deployed in Hong Kong waters from June 25, 2018 to July 11, 2019 and compared those to the line transect data collected by the HKCRP during the same time period.

Materials and Methods

Acoustic data collection

C-POD data were collected as part of an ongoing PAM study conducted by HKCRP to better understand how humpback dolphins are using the waters around Hong Kong. For this work, we used the first full year of data from twelve C-PODs deployed throughout humpback dolphin habitat in Hong Kong waters from June 25, 2018 to July 11, 2019 (**Fig. 1**). The C-PODs were fixed horizontally to a metal frame (80cm x 80cm) which sat on the sea floor. C-PODs were retrieved and then redeployed by professional divers every two to four months to exchange batteries and SD cards.

Acoustic data analyses

C-POD files were analyzed using CPOD.exe version 2.044 (Chelonia Ltd, UK). The data were processed through KERNO and GENENC, two automated classifiers within the software. The KERNO classifier filters for clicks that belong to a train (at least five clicks) and classifies them into four different categories: Narrow Band High Frequency (NBHF, porpoise), other cetaceans (dolphin), sonar, and Weak Unknown Train Source (WUTS). The classifier also provides a quality class assessment for each click train: high, moderate, low, and doubtful, which is an assessment of the chance of the train coming from a non-train source. The GENENC classifier filters the files for click trains that belong to dolphins ("other cet") and helps to remove false positives and improve classification. All click trains belonging to "Other cet" with the minimum Source Pressure Level (SPL) set to 50 to help reduce noise in the advanced train filters in the files section of the CPOD.exe software were exported as Detection Positive Minutes (DPMs), combined and imported into a MySQL database.

Sighting data

All datasheets from vessel surveys between June 25, 2018 and July 11, 2019 completed by the HKCRP survey teams were obtained. Surveys were conducted as described in Hung (2019). Briefly, a survey team consisted of a data recorder and primary observer on a 15m vessel who surveyed from a flying bridge area approximately 4.5m above the water surface. The vessel travelled at a constant speed of 13-15km per hour along the transect lines (see Figure 2). The primary observer searched for dolphins with marine binoculars (7 x 50 Fuijinon) while the data recorder searched with unaided eyes and filled out the datasheets. Additional observers (one or two) were available to rotate-in at 30-minute intervals to minimize fatigue of the survey members. When a sighting was made, the team would end survey effort and record the time, initial sighting distance and angle to the dolphin from the vessel. The vessel would then leave the trackline and slowly approach the dolphins to collect photo-identification data and collect data on group size, group composition and behaviour.

Hand-written line-transect data from the datasheets were transcribed into excel files, which were then imported into a MySQL database. Subsequently, each day was read into R and plotted onto a map of the area to determine when the boat travelled within 1000m of a C-POD and where dolphin sightings occurred relative to C-POD positions. A function was created in R to calculate the initial dolphin position based on the boat position, sighting angle and distance to the dolphins at the time of the first sighting. An additional function was made to calculate the distance between two coordinates to calculate distances of a dolphin sighting to a C-POD or a boat position to a C-POD.

Filtering Data for Comparison

There were three scenarios across which the visual and acoustic data were compared: (1) dolphins detected by both methods, (2) dolphins detected acoustically but not visually, and (3) dolphins detected visually but not acoustically. We did not consider scenarios where dolphins were not detected with either method because such scenarios do not provide data on the relative performance of either method.

Scenarios where dolphins were detected by both methods were identified by those occasions where dolphins were detected acoustically at a C-POD and visually seen within 1000m of the C-POD within a 10-minute window of each other. A 10-minute window was chosen with the hope to detect the correct group of dolphins as they pass through the C-POD area. The vessel can cover the area in approximately 6-10 minutes and since we were unaware of the direction the dolphins were moving when sighted, we created the time window: five minutes before and five minutes after the time of the sighting. For these scenarios, the sighting data were used to calculate the distance of the dolphin(s) to the C-POD. The number of dolphins sighted was also recorded.

Scenarios where dolphins were detected acoustically but not visually were identified by those occasions where dolphins were detected by the C-PODs, the vessel surveyed within 1000m of the C-POD within a 10-minute window of the acoustic detection, but did not visually detect dolphins. Group size data were not available for such detections, because the dolphins were only detected acoustically.

Scenarios where dolphins were detected visually but not acoustically were identified by those occasions where the vessel made a sighting of dolphins within 1000m of a C-POD, but the

C-POD did not have any acoustic detections within a 10-minute window of the visual detection. For these scenarios, the distance of the dolphins to the C-POD was calculated and recorded, as was the group size of the dolphins.

Results

During the time period between June 25, 2018 and July 11, 2019 there were 653 occasions where the vessel surveyed within 1000m of a C-POD, on 93 of which dolphins were detected by one or both methods. On 8 occasions (~8.6%) dolphins were detected both visually and acoustically, on 76 occasions (~81.7%) dolphins were detected visually but not acoustically and on 9 occasions (~9.7%) dolphins were detected acoustically but not visually. Given the low amount of detections made both acoustically and visually, it was not possible to estimate a detection curve for the C-PODs.

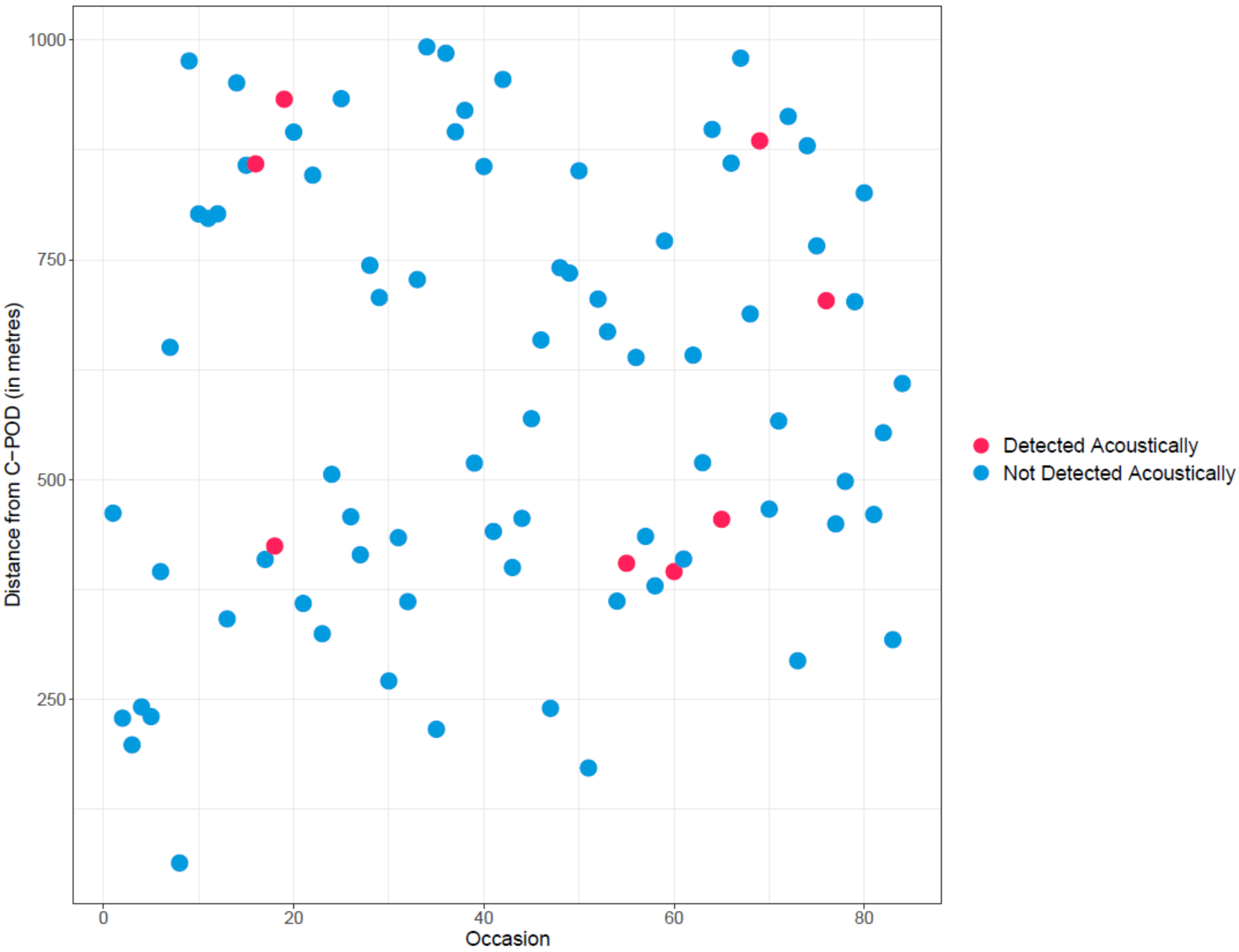

Figure 3: Distances of dolphins to the C-POD by occasions where dolphins were detected visually and acoustically (n = 8, red), and occasions where dolphins were detected visually but not acoustically (n = 76, blue).

There was not a strong relationship between the distances of dolphins to the C-POD and whether or not they were acoustically detected (**Fig. 3**), although dolphins who were not acoustically detected tended to be slightly further away from the C-POD than those that were detected (**Fig. 4**). Group size was larger in cases were dolphins were acoustically detected than in cases where they were not (**Fig. 5**, p = 0.0497). The mean beaufort sea state on occasions where dolphins were detected acoustically but not visually (2.33) was not higher than occasions when dolphins were detected visually (2.36).

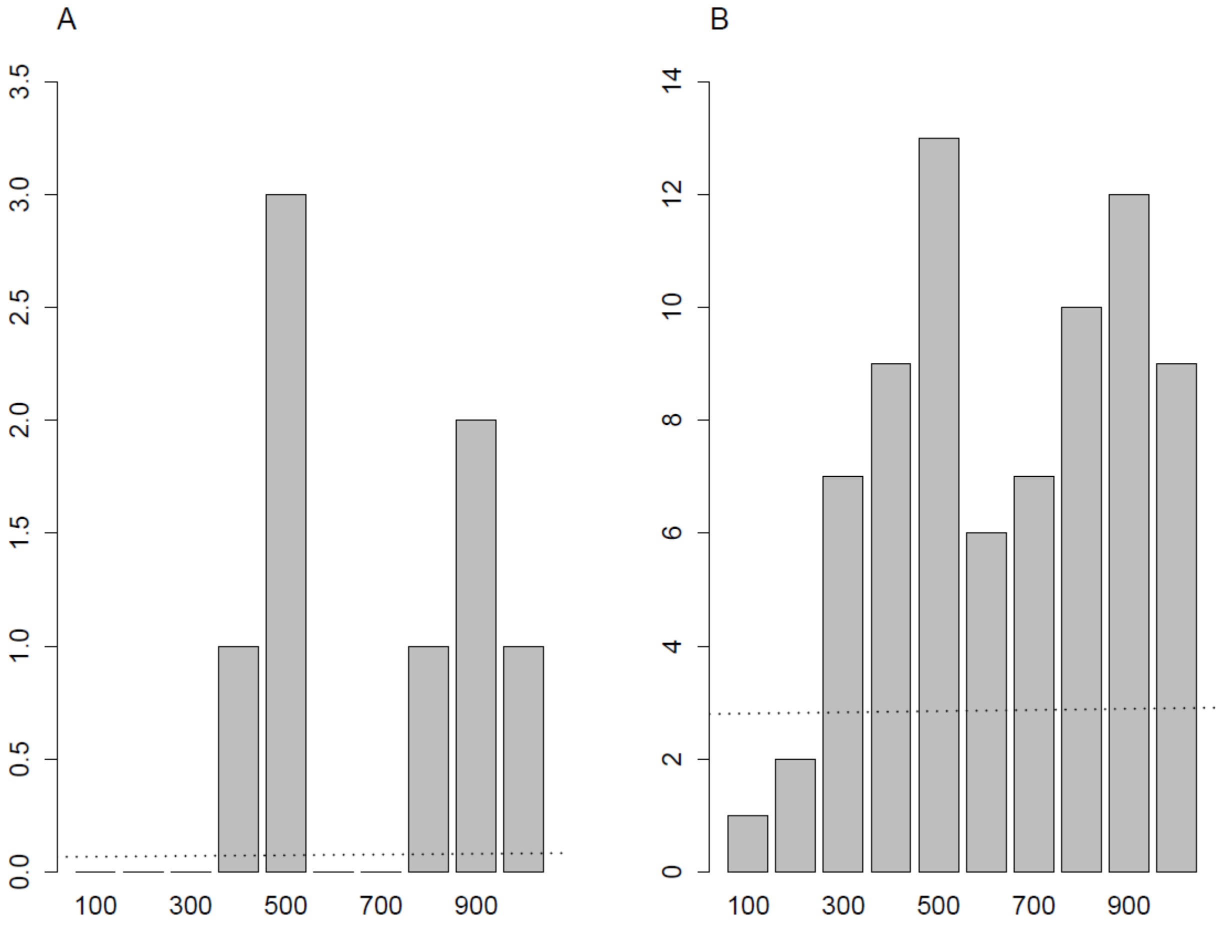

Figure 4: Distance from the C-POD (in metres) and frequency (number of occasions) for A: Dolphins detected visually and acoustically (n = 8) and B: Dolphins detected visually but not acoustically (n=76). Dotted line represents the regression line, A (estimate = 0.0013, Std. Error = 0.0011, t-value = 1.2, p-value = 0.26), B (estimate = 0.0087, std. error = 0.0033 t-value = 2.6, p-value = 0.031).

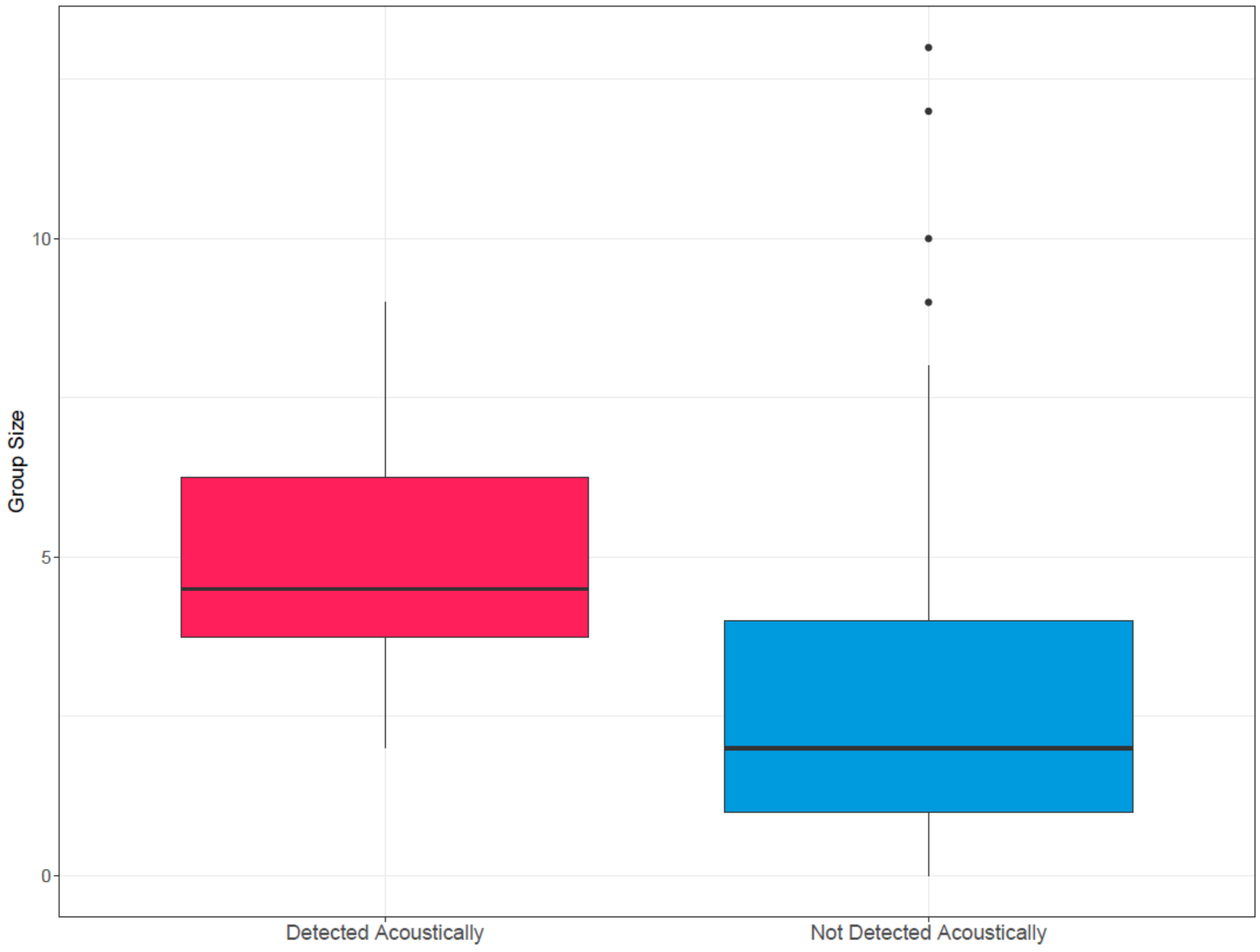

Figure 5: Dolphin group size when dolphins were detected visually and acoustically (n = 8, pink) and when dolphins were detected visually but not acoustically (n = 76, blue). Mean group size of dolphins detected acoustically is 5, while it was 3.1 for dolphins not detected acoustically. Sig. test (estimate = -1.9, std. error = 1.0, t-value = -2.0, p-value = 0.049). Welch two sample t-test (t = 2.2, df = 9.0, p-value = 0.054).

Discussion

C-PODs have shown to be a successful device to detect humpback dolphins and provide important data on their habitat use in Hong Kong waters (Chapter 2). However, here we found very little overlap between acoustic and visual detections. From the 93 occasions of which dolphins were detected by one or both methods, dolphins were detected visually but not acoustically the most often (76 occasions), followed by acoustically but not visually detected (nine occasions) and were detected by both methods (eight occasions). These data suggest that, when both survey methods are available, visual surveys are more effective at detecting dolphins than the C-PODs. However, visual surveys are severely limited in terms of both time, space, and conditions, whereas multiple C-PODs can continuously collect data from multiple locations for months at a time, regardless of environmental conditions. Due to the murky coastal waters of Hong Kong, we had originally assumed that humpback dolphins would be echolocating frequently to aid in orientation. However, the lack of acoustic detections when dolphins were known to be present indicates either that the dolphins are not echolocating frequently or that other factors are limiting the ability of the C-PODs to detect the echolocation clicks.

Dolphin clicks are highly directional, therefore if dolphins are close to the C-POD but not facing directly toward the device, their echolocation clicks may not be logged. It is possible that there are many times dolphins were within the effective detection distance of the C-POD and echolocating, but the click trains were not detected or did not meet the stringent criteria of the software. When odontocetes use echolocation, the majority of the energy is contained in a very narrow forward beam (~±30°) and this becomes less focused past this angle (Au et al., 2012; Macaulay et al., 2020). Therefore, if dolphins are within the effective detection distance of the C-POD but not facing within ±30° towards the device when they echolocate, their clicks are likely not being detected.

The environment also impacts the ability of C-PODs to detect clicks. Humpback dolphins in Hong Kong spend much of their time in shallow waters (<20m) close to shore. In shallow water, distortion of intense clicks can occur as they can be reflected both off the seabed and surface (Zimmer, 2011), creating a complex mixture of direct and reflected clicks at the C-POD that may limit the ability of the software to identify clear click trains. For example, Nuuttila et al.

(2013b) found that in shallow waters clicks may be received by the C-PODs from many different directions and may result in the device not identifying them as click trains. In addition, due to the C-POD's algorithm of click train detection, individual clicks will always go undetected (Nuuttila et al., 2013b). Therefore, there are likely many times only partial click trains, or complex mixtures, reach the C-POD and therefore do not get properly classified. To determine the rate of these types of false negatives, every minute of the CP1 file would need to be visually validated to look for fragments of true click trains. This would be difficult to perform, especially on such a large data set as available for this study.

With Hong Kong being one of the busiest ports in the world, noise and vessel traffic are impacting dolphin movement (altering diving times and behavioural states) and could also mask dolphin sound production (Pine et al., 2017; Piwetz et al., 2012; Sims et al., 2012). A study that assessed the indirect impacts of boat traffic on humpback dolphins in Moreton Bay, Australia found that vessels passing by did not affect the rates at which dolphins produced click trains and burst pulse vocalizations (Van Parijs & Corkeron, 2001). Even if the rates at which dolphins produce click trains remains unchanged, the increased noise likely affects the C-POD's ability to reliably detect click trains. For example, in Hong Kong waters, Sims et al. (2012) detected vessel noise during over 60% of any given day in their study period. Greater vessel traffic is associated with raised background noise levels with higher source pressure levels across most frequencies (Pine et al., 2017; Sims et al., 2012). Sound pressure levels varied around Lantau Island with the South Lantau Vessel Fairway having the highest levels with high speed ferries making hundreds of trips in this area daily (Sims et al., 2012). Sims et al. (2012) found some vessel sounds at distances greater than or equal to 100m from dolphinshave the ability to mask their communicationsounds (as detected by hydrophones, rather than C-PODs). How noise may be affecting the ability of the C-POD to detect dolphins in these waters needs further investigation. When noise levels and harbour porpoise click trains were simultaneously recorded on both C-PODs and another PAM recorder in Danish waters, a decrease in detections was seen as noise levels increased (Clausen et al., 2019). However, click detection differences were larger on the C-POD data across three-filters compared to Pamguard (Clausen et al., 2019). Placing a broadband hydrophone such as a SoundTrap directly beside the C-PODs would provide a better understanding the acoustic environment and allow for noise level comparison across C-POD locations.

Dolphins detected acoustically and visually had a larger mean group size than those detected visually but not acoustically. In theory, a larger group size could increase the chance that a click train will be detected. But in groups of bottlenose dolphins, echolocation production per dolphin was found to decrease with increased group size and single dolphins were known to echolocate at a higher rate than dolphins in a group (Nuuttila et al., 2013b). Also, overlapping clicks among a dolphin group may reduce the chances of a click train being detected (Nuuttila et al., 2013b). Similar to group size, dolphin behaviour also has an effect on echolocation activity. Nuutilla et al. (2013a) found a higher detection probability for bottlenose dolphins and harbour porpoises when they were feeding than when travelling. Nuutilla et al. (2013b) also found that the average effective detection radius of feeding bottlenose dolphins (449 m, 95% CI: 211 – 497 m) was greater than that for travelling dolphins (317 m, 95% CI: 211 – 497 m). However, the opposite was found for single animals where single traveling dolphins were found to have a higher detection probability than single feeding dolphins (Nuuttila et al., 2013b). Therefore, both group size and behavioural state are also likely contributing to the probability that dolphins will be detected.

Prior to the the PAM project in Hong Kong using C-PODs, data were limited primarily to visual surveys. Here, little overlap was found between visual and acoustic detections. These results may suggest that, at least in Hong Kong waters, the echolocation characteristics of humpback dolphins make visual surveys more effective than acoustic surveys. However, the C-PODs are still able to provide data at times when visual surveys are not possible, as well as simultaneously survey many areas, and therefore represent a valuable source of information. The acoustic data provide an opportunity to study these dolphins at times where visual surveys are not possible such as during the night and in poor weather conditions, providing a finer-scale understanding of dolphin habitat use (Chapter 2).

Conclusion

Passive acoustic monitoring using C-PODs has added important knowledge to our understanding of habitat use in Hong Kong waters. Surprisingly, when the visual and acoustic data were compared, there was little overlap between the two detection methods. It seems visual surveys are more effective at detecting dolphins when present; however, they are limited in both space and time. The addition of acoustic surveys via C-PODs, which can continuously and simultaneously survey many areas, therefore still represents a valuable tool for long-term population monitoring.

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CHAPTER 4

General Conclusion

Passive acoustic monitoring of Indo-Pacific humpback dolphins (*Sousa chinensis chinensis*) in Hong Kong waters has enhanced our understanding of their habitat use. With observational data showing an evidence of a decline in dolphin abundance since the late 1990's, in addition to a shift in their distribution, obtaining a finer scale understanding of how dolphins are using Hong Kong waters is important. These data should be helpful in guiding conservation and research efforts in the future.

From the twelve C-PODs deployed from June 2018 to July 2019, we were able to obtain information on diel, seasonal and geographic patterns in acoustic activity. Location was found to have the largest effect on the probability of detections. The proportion of acoustic detections by location coincided well with visual surveys with the greatest numbers in locations around southwestern Lantau Island. Importantly, dolphins were also detected fairly regularly, but in low numbers, in northeast Lantau where they have been rarely sighted in the last several years. Time of day and season also had significant effects on the probability of detections, but these effects differed greatly by location.

When visual and acoustic data were compared there was surprisingly little overlap between the two detection methods. Dolphins were most frequently detected visually but not acoustically. With so few detections made by both visual and acoustic methods, it was not possible to estimate a detection curve for the C-PODs. Dolphins that were not detected acoustically tended to be slightly further away from the C-POD, while group size was larger in cases where dolphins were acoustically detected than in cases where they were not. Both the environment (vessel traffic, noise, and acoustic disturbance due to shallow water) and the high directionality of dolphin echolocation clicks are likely factors influencing the ability of the C-POD to detect dolphins in Hong Kong waters. Group size and behaviour of the dolphins also likely affect the probability of detecting dolphins. Although C-PODs did not seem as effective at detecting dolphins as visual surveys, they remain an important contribution to long-term population monitoring due to their spatial and temporal coverage.

Future work

One major limitation of this work is that it is based on only one year of data (June 2018-July 2019). As such, it is difficult to determine how representative the data are regarding humpback dolphin habitat use in Hong Kong waters as a whole and how many patterns may be specific to just that particular year. For example, with each “season” represented only once, it is possible that the patterns I found were specific for this one particular year, and data from more years are needed to determine if these patterns are stable over time. It would therefore be interesting to extend these efforts to future years to see if and/or how the geographical, seasonal and diel patterns remain, or change, over time.

It was surprising that so many dolphins were not detected acoustically when there was a visual sighting. The environment (noise, vessel traffic, shallow waters) and the high directionality of echolocation clicks were likely causes for not detecting the dolphins. Setting up a number of controlled experiments in Hong Kong waters with the C-PODs using playbacks of humpback dolphin echolocation clicks would make it possible to examine these potential causes. For example, it would be interesting to use playbacks of echolocation clicks to examine how the shallow waters may cause clicks to become distorted due to their reflection off the bottom and surface of the water, which would render these clicks undetectable by the C-PODs. Such controlled experiments would provide important information regarding how the environmental conditions around Hong Kong influence C-POD detections in this area, specifically. Moreover, similar playback experiments could be used to better assess the degree to which background noise may be influencing detections. For example, C-PODS and hydrophones could be placed in areas with different levels of background noise (such as that from the high-speed ferries), to assess how this background noise influences the ability of the C-PODS to detect playbacks of echolocation clicks. Using a playback experiment would also aid in determining the effective detection radius of C-PODs in these waters by testing the ability of the device to detect clicks at varying distances. Experimenting with the directionality of the playbacks relative to the C-POD would provide insight on how the orientation of a dolphin effects the likelihood of detections and at what angles the C-POD is able to detect clicks. Additionally, using the known feeding click characteristics (rapid reduction of inter-click intervals) recorded by the C-PODs could be used to determine location and times when dolphins may tend to forage more frequently and help identify important foraging patterns.

Overall, although C-PODs were not as effective at detecting dolphins as visual surveys, they remain an invaluable contribution to the conservation of humpback dolphins in Hong Kong waters by detecting dolphins throughout their habitat simultaneously and at times when visual surveys are not possible.