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Impact of pile-driving on Hector's dolphin in Lyttelton Harbour, New Zealand

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ABSTRACT

Several dolphin species occur close inshore and in harbours, where underwater noise generated by pile-driving used in wharf construction may constitute an important impact. Such impacts are likely to be greatest on species such as the endangered Hector's dolphin (*Cephalorhynchus hectori*), which has small home ranges and uses this habitat type routinely. Using automated echolocation detectors in Lyttelton Harbour (New Zealand), we studied the distribution of Hector's dolphins using a gradient sampling design over 92 days within which pile-driving occurred on 46 days. During piling operations, dolphin positive minutes per day decreased at the detector closest to the piling but increased at the mid-harbour detector. Finer-grained analyses showed that close to the piling operation, detections decreased with increasing sound exposure level, that longer piling events were associated with longer reductions in detections, and that effects were long-lasting - detection rates took up to 83 h to return to pre-piling levels.

1. Introduction

The increase in anthropogenic noise in the ocean (e.g. McDonald et al., 2008) has resulted in growing interest in researching the impact of noise on marine mammals, in particular cetaceans. Since cetaceans rely on sound for foraging and sociality, it is important to know how the additional noise may affect them. Negative impacts on marine mammals have been observed from sources including airgun pulses used in seismic surveys (e.g. Romano et al., 2004; Lucke et al., 2009; Gray and van Waerebeek, 2011), shipping (Aguilar Soto et al., 2006; Castellote et al., 2012; Rolland et al., 2012) and sonars (e.g. Fernández et al., 2005; Filadelfo et al., 2009; Tyack et al., 2011). Pile-driving, another source of underwater noise pollution, is of special concern since the noise is loud, impulsive and broadband in frequency (Madsen et al., 2006). Effects on endemic, endangered species, especially those with small home ranges, are of particular interest in this context.

Harbour porpoise (*Phocoena phocoena*) has very similar acoustic behaviour (Dawson, 2018; Dawson and Thorpe, 1990; Villadsgaard et al., 2007) to Hector's dolphin, and is similar in size and ecology (Würsig et al., 2018). Harbour porpoises show strong avoidance reactions to pile-driving noise (Carstensen et al., 2006; Thompson et al., 2010; Tougaard et al., 2009; Brandt et al., 2011; Brandt et al., 2016). These studies used passive acoustic monitoring devices (T-PODs or C-PODs) at increasing distances from the piling to investigate changes in detection rates of echolocation clicks. Tougaard et al. (2009) and Brandt et al. (2011) found a marked decrease in porpoise clicks over a radius of at least 20 km from the piling. At close range (2.6 km from the source), this response lasted up to 72 h after piling ceased (Brandt et al., 2011). Aerial surveys confirmed that porpoises actually left the area rather than becoming silent (Dähne et al., 2013). Piling noise also affected echolocation rate, however, as a sudden decrease in click rate was observed following the onset of piling (Brandt et al., 2011).

Broadly similar responses have also been observed in Indo-Pacific bottlenose dolphins (*Tursiops aduncus*) in Fremantle Harbour, Australia. Video recordings made in a harbour channel showed significantly fewer visual detections during pile-driving activity for wharf construction (Paiva et al., 2015). This study could not, however, determine whether decreased detections were due to decreased use of that habitat. Alternative explanations include that masking of communication signals may have led to reduced surface socialising, that detection of prey by echolocation may have been impeded, and/or that the effect of pile-driving may have been indirect (e.g. on prey abundance or their availability).

Hector's dolphin (*Cephalorhynchus hectori*), is an endangered delphinid found only in New Zealand. This species uses high frequency click trains for echolocation and communication. These clicks are about 140 ms in duration and most are centred at a frequency of 125 kHz (Dawson and Thorpe, 1990). Hector's dolphin signals are low-level

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compared to those recorded from other cetaceans, with an estimated peak-to-peak source level of 161–187 dB re 1 μPa @ 1 m (Kyhn et al., 2009). For harbour porpoise this is 178–205 dB re 1 μPa @ 1 m (Villadsgaard et al., 2007). There are no data on the hearing sensitivity of Hector's dolphin.

Hector's dolphin have one of the smallest documented home ranges of any dolphin species (Rayment et al., 2009a) and favours inshore waters, frequently entering harbours (Dawson et al., 2013). The principal threat to the species, incidental catch in gillnets and trawls, resulted in the establishment of the Banks Peninsula Marine Mammal Sanctuary in 1988, and 20 years later, extensive further closures to gillnetting (Slooten and Dawson, 2010).

Construction work for the development of Port Lyttelton, in anticipation of a growing increase in container cargo, was combined with earthquake repair work. This work included 15 months of pile-driving, and more is scheduled for 2019. Hector's dolphins are routinely present in Lyttelton Harbour (Brough et al., 2014, in press; Leunissen and Dawson, 2018). Pile-driving could be an additional impact on Hector's dolphin and provides the context for this study. Underwater recordings made in Lyttelton Harbour at close range to the piling (up to 370 m) show broadband, impulsive strikes with high peak-to-peak SPLs. Maximum calculated source sound exposure level (SEL) was 192 dB re 1μPa^{2}s @ 1 m (zero-to-peak sound pressure level ($SPL_{0\text{-}p}$) of 213 dB re 1 μPa @ 1 m: Leunissen and Dawson, 2018). All three drivers produced a similar distribution of energy across the frequency range, the highest energy was around 200–300 Hz. While most energy was between 50 Hz-10 kHz, there was some energy to at least 100 kHz (Leunissen and Dawson, 2018).

Since Hector's dolphins have small home ranges, and the pile-driving in Lyttelton occurred within a confined harbour environment, there is a high chance that this operation had a significant impact on the local Hector's dolphins. In a previous paper we provided measurements of the pile-driving sounds and their propagation within this harbour environment (Leunissen and Dawson, 2018). In this study we attempt to measure impact on the dolphins' distribution within Lyttelton Harbour. In particular, does the detection rate change after a pile-driving event? If there is an effect, how long does this last following the pile-driving event?

2. Methods

2.1. Field techniques

Pile-driving was used extensively in the reconstruction of one of the main wharves (Cashin Quay 2) in Lyttelton Harbour, New Zealand (43.6033° S, 172.7227° E) (Fig. 1). Piles were driven within an area 77 m long (along the wharf) and 24 m wide (see ‘Pile-driving’ in Fig. 1). This area contained 90 pile locations, of which 57 were driven during our study (between December 19th, 2014 and March 25th, 2015). Three different pile drivers were used with hammer weights of nine, ten and 14 t, with a maximum blow energy of 206 kJ. The hollow steel piles had diameters of 0.61 or 0.71 m, and were driven an average of 66 m into the seabed (HEB construction, pers. comm. 2015). A “soft start” using the hammer on its lowest energy setting for the first 2 min, was standard practice (i.e. required by the pile-driver manufacturers).

Echolocation detectors (v.5 T-PODs, numbers 755, 775 & 776, Chelonia Ltd) were moored in Lyttelton Harbour from December 19th, 2014 to March 25th, 2015, 2 m from the seabed, at distances of 1300, 2000, and 6150 m respectively from the piling. This deployment follows a gradient sampling design (Thompson et al., 2010; Brandt et al., 2011) and enables detection of temporal effects with distance. The sites were chosen to represent inner, mid and outer harbour sites (Fig. 1) while considering the safety of our equipment for long term deployment in a busy harbour. The inner T-POD at 1300 m was, therefore, at the closest practical distance to the pile-driving. The inner and mid T-PODs were moored near existing harbour markers. The outer T-POD was moored in a bay well clear of shipping traffic, with a buoy at the surface (see Table 1 for properties of the sites where T-PODs were moored).

T-PODs were serviced (data downloaded, batteries replaced, fouling removed) on 7 January 2015 (re-deployed on the same day) and 27 February 2015 (re-deployed on 5 March 2015 due to unsuitable weather conditions). The same T-PODs were used at their respective sites for the entire monitoring period, except for the outer site. The outer T-POD became detached from its mooring between 7 January and 27 February, and was not recovered. This T-POD was replaced with a new device (v.4 No. 484, Chelonia Ltd). The aim of acoustic monitoring was to detect changes in acoustic activity in relation to pile-driving noise. Sensitivities of the T-POD versions used in the current study (v. 4 and 5) are similar and much more standardised than previous versions (Dähne et al., 2006; Verfuß et al., 2008). Hence, any differences in detection rates are likely negligible (see also Dawson et al., 2013).

In all T-POD deployments, five scans were optimised for detection of Hector's dolphins (target filter frequency = 130 kHz; reference frequency = 92 kHz; bandwidth = 4; noise adaptation = + +; sensitivity = 10; scan limit = 240). One scan was set at a lower frequency to discriminate between Hector's dolphins and other delphinids (target filter frequency = 50 kHz; reference frequency = 70 kHz; sensitivity = 6). The same settings were used as in Dawson et al. (2013) studying Hector's dolphin habitat use and Rayment et al. (2011) detecting Maui's dolphin (*Cephalorynchus hectori maui*) clicks. Other studies using T-PODs employed a similar strategy to discriminate between detections of harbour porpoises and bottlenose dolphins (e.g. Philpott et al., 2007; Bailey et al., 2010). The detection radius of T-PODs detecting Hector's dolphins is 198–239 m (Rayment et al., 2009b).

Pile-driving noise levels were recorded continuously throughout the study via a DSG recorder (Loggerhead Instruments; HTI-96 min hydrophone, max. Frequency response 2–30 kHz) moored in Diamond Harbour (see Fig. 1). This recorder was set to sample at 2500 Hz to allow an extended recording period. While this sample rate could not capture the full spectrum of piling noise (i.e., only up to 1250 Hz), the recordings allowed incorporation of relative intensity of pile-driving noise into the statistical analysis of echolocation detections.

Noise levels were measured and modelled throughout the harbour (see Leunissen and Dawson, 2018 for more detail). The sound levels at each T-POD location are summarised in Table 1.

2.2. Analyses

TPOD data were processed using the manufacturer's software (T-POD.exe v8.24). This software classifies clicks according to the likelihood they were of cetacean origin. The categories CET HI and CET LO (combined as ‘Cet All’) reliably represent Hector's dolphin detections (Rayment et al., 2009b), and are used here. Using only ‘Cet All’ detections, however, results in a conservative account of habitat use as many genuine trains are classified as DOUBTFUL (Rayment et al., 2009b; see also Thomsen et al., 2005, for a similar result from harbour porpoise).

Click data were exported as detection positive minutes (DPM) per hour - the number of minutes per hour in which dolphin clicks were detected, and DPM per day – the number of minutes per day in which dolphin clicks were detected. DPM (measured over a given time period) is the recommended metric for studying habitat use and behaviour (Chelonia Ltd. 2007), has been used in other studies assessing impacts of pile-driving (Brandt et al., 2011, 2016; Degraer et al., 2012), and has the advantage of reducing the effect of variation in sensitivity among T-PODs (Dähne et al., 2006). The DPM per hour measure allowed tracking of the post pile-driving echolocation activity on a fine temporal scale.

Mean SEL was used to account for pile-driving strike intensity. It was generally not possible to calculate the SEL for every strike within an hour, due to variation in ambient noise (such as water flow noise or passing boats). Therefore, a representative sample of ten pile strikes was used to calculate the mean pile strike SEL for each hour. The

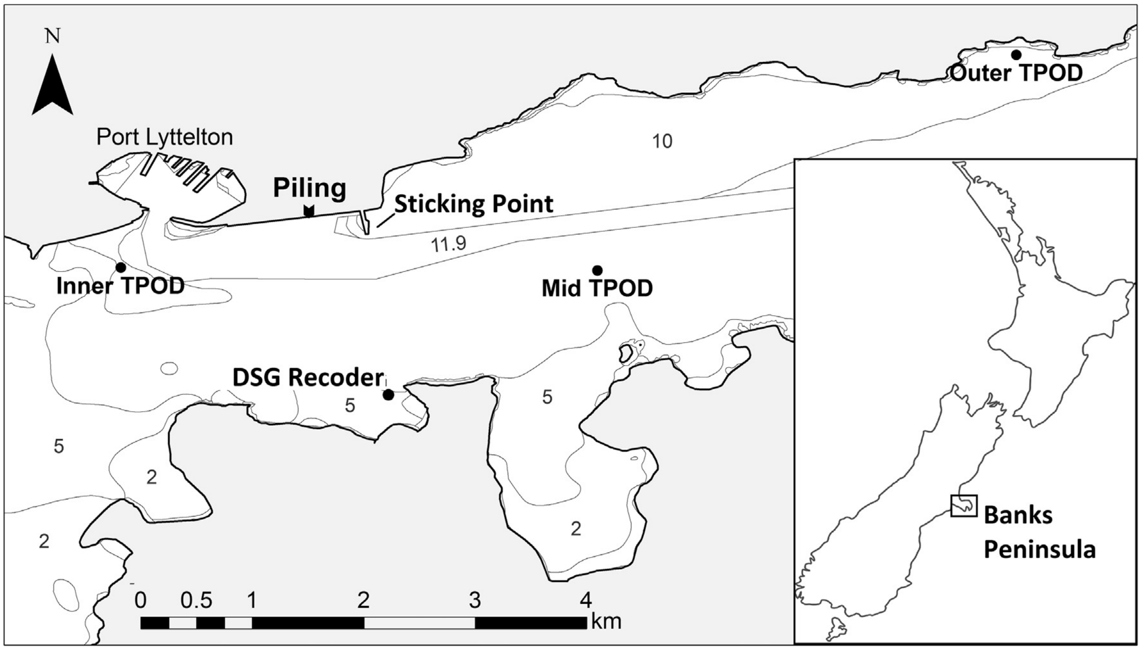

Fig. 1. Locations of T-POD monitors, DSG recorder and pile-driving in Lyttelton Harbour. Numbers within gray contour lines indicate depth (m). Inset: Map of New Zealand.

Table 1
Site properties for each T-POD location. Substrate information obtained from Chart NZ 6321 (www.linz.govt.nz).

Site	Range to piling (m)	Range to nearest shore (m)	Substrate	Water depth (m)	SEL (mean, max; dB re 1μPa^{2}s)	SPL_{0p} (mean; dB re 1μPa)
Inner	1300	330	Mud/Shell	4	127, 137	158
Mid	2000	890	Sand/Mud/Shell	8	114, 124	145
Outer	6150	125	Mud	7	90, 100	121

sample was chosen (through visual inspection of the hour's waveform in Audacity) to avoid strikes masked by ambient noise, and such that the peak pressure in the strikes' waveforms were at midrange of the peak pressures of all strikes within the hour. Peak pressure was proportional to SEL (Leunissen and Dawson, 2018). SEL per day was calculated as the mean across all hours which contained pile-driving. To quantify how long any effect lasted following a pile-driving event (where a new event was defined when the time between consecutive strikes, from one pile driver, exceeded 1 min), the variable "time-since-piling" was included. The duration of previous pile-driving events was also included. For each hour this was calculated as the total piling-positive-minutes (PPM) within previous consecutive hours containing pile-driving, up to the current hour. The duration of piling per day was calculated as total PPM across all hours for that day. Hourly wind data were provided by Metservice (www.metservice.com). This variable was relevant because in shallow water sound does not propagate as far at high wind speeds due to decreased reflection at the roughly textured water surface (Norton and Novarini, 1996). Increasing aeration of the water also reduces propagation (Mallock, 1910). This could lead to lower click detection rates at higher wind speeds (e.g. Brandt et al., 2016). Time of day and time since high tide were included in our models as they have been shown to influence Hector's dolphin distribution in Akaroa Harbour, on the south side of Banks Peninsula (Dawson et al., 2013).

2.3. Statistical analyses

Statistical analyses were carried out using the software package R (v 3.2.4, The R Foundation for Statistical Computing, 2016). The effect of pile-driving noise on dolphin detections was investigated using an information theoretic approach (Anderson et al., 2000; Burnham and Anderson, 2002), by comparing a suite of competing explanatory models. The two response variables were DPM per hour and DPM per day. Response variables were not normally distributed. Visual comparison of fitted Gaussian, Poisson and negative binomial distributions, and Q-Q plots indicated that the negative binomial distribution provided the closest fit to both response variables.

Explanatory variables consisted of piling-related, time-related and environmental variables (Tables 2 and 3). Collinearity among explanatory variables was assessed using variance inflation factors (VIFs). A cut-off value of three (Zuur et al., 2011), was not exceeded, indicating that collinearity was not significant.

A 17 day hiatus in pile-driving over the Christmas-New Year period was much longer than any other break in piling activity (max. 90 h). The DPM per hour dataset was restricted to include data for which time-since-piling did not exceed 150 h. This limit is more than twice as long as the longest duration of impact observed in harbour porpoise studies (72 h; Brandt et al., 2011).

The effect of explanatory variables on response variables was investigated using Generalised Additive Models (GAMs; Hastie and Tibshirani, 1990) with a negative binomial response (using the package *mgcv* in R). GAMs fit a sum of smooth functions for each covariate, and are particularly useful for modelling the non-linear relationships between cetacean distribution and environmental variables (Ferguson et al., 2005; Torres et al., 2008; Embling 2009). Since the model is additive, the effect of each covariate is considered in addition to the effects of the other covariates (Hastie and Tibshirani, 1990). The choice of basis dimension for smoothing terms was not restricted and left to be chosen during the modelling process for best fit.

Explanatory variables were expected to have a different effect on the response variable based on T-POD location. Therefore, a factor

Table 2
List of explanatory variables used in the models of DPM per day.

Variable (abbreviation)	Type	Description
Piling related variables		
Sound Exposure Level (SEL)	Continuous	Mean sound exposure level (dB re 1 μPa^{2}s) for each day as measured at the Diamond Harbour DSG
Piling positive minutes (PPM)	Continuous	Total number of minutes that contained pile-driving noise each day
Time related variables		
Previous DPM (DPMt-1)	Continuous	DPM measured during previous day.
Environmental variables		
Wind speed (Wspd)	Continuous	Measured in knots at 9 am each day
Wind direction (Wdir)	Continuous, cyclic	Measured in degrees at 9 am each day
T-POD position (TPOD)	Factor, 3 levels	Inner (1), mid (2) or outer (3) harbour position

interaction term (using the tensor product interaction function *ti* with the 'by = TPOD' argument), which fitted a separate smoothing function for each of the three T-POD locations, was also tested (as well as testing a smoothing function *s* for each variable across all T-POD locations combined). Models never contained both the smoothing function of the variable and the factor interaction term as this would include the same variable twice. All smoothed functions were fitted using the default spline (cubic regression spline for *ti* and thin-plate regression spline for *s*), except for the circular variables (tide, time of day and wind direction). These variables were fitted with a cyclic cubic regression spline.

Response variables were temporally auto-correlated (tested using the auto-correlation function *acf* in the R package *stats*). One method to account for correlation is to use a correlation structure in a Generalised Additive Mixed Model (GAMM). For our data, this approach (using a corAR1 structure) produced marginal reductions in temporal autocorrelation, and produced models for which normality was not satisfied (verified via Q-Q plots). Instead, we introduced an explanatory variable with the value of the response at a previous point in time (in this case DPM of the previous hour or day; Tables 2 and 3), an approach used by Brandt et al. (2016) in their T-POD study of pile-driving effects on harbour porpoise. This considerably reduced the effect of temporal autocorrelation in the resulting models (see Appendix A).

A suite of GAMs was constructed and their performances compared via AICc. Model selection was conducted using forward step-wise selection (see Zuur et al., 2009). The Akaike weight was also calculated for each model, and can be interpreted as the approximate likelihood that the model is the best in the set (Anderson et al., 2000). The index of relative importance (IRI) was used to rank the importance of each variable (Burnham and Anderson, 2002). While model averaging can be useful for linear regression models, averaging structural parameters in some non-linear models is not recommended (Burnham and Anderson, 2002). Also, the coefficients for the categorical variable (T-POD) were very similar across all top models. Hence, we have not presented any model averaged results.

An interaction between time-since-piling (TSP) and duration-of-piling (Dur) was included in the modelling of DPM per hour. This was done to investigate if piling events of longer duration increased the length of time that detection rates were affected after piling. A contour plot was used to illustrate the effect of this interaction. This required all other explanatory variables to be fixed. SEL and DPMt-1 were fixed at their respective mean values, and Hour, Tide and Wdir were fixed at values at which DPM per hour at the inner harbour was predicted to be high by the models (i.e. when dolphins were likely to be present in the inner harbour).

Relationships were considered statistically significant at alpha = 0.05. Model validity was verified using diagnostic plots (Q-Q plots and histograms to check normality, residuals vs linear predictor to check heterogeneity, and response vs fitted values to check model fit, using randomised quantile residuals to account for the negative binomial distribution).

3. Results

This study consisted of 92 days of T-POD monitoring at the inner and mid sites, and 41 days at the outer site (Table 4), yielding a combined total of 5256 T-POD hours. During this period pile-driving occurred on 46 days, with a mean of 125.5 mins of piling per day (SE = 16.7 mins). This average excluded the 17-day break over

Table 3
List of explanatory variables used in the models of DPM per hour.

Variable (abbreviation)	Type	Description
Piling related variables		
Sound Exposure Level (SEL)	Continuous	Mean sound exposure level (dB re 1 μPa^{2}s) of a representative sample of 10 strikes per hour as measured at the Diamond Harbour DSG
Time since piling (TSP)	Continuous	Equals '0' during hours of piling, otherwise equals the minutes since the previous piling event.
Piling duration (Dur)	Continuous	Duration of the previous piling event in minutes.
Time related variables		
Hour of day (Hour)	Continuous, cyclic	Equals '0' for the hour starting at 00:00 am, to '23' for the hour starting at 11:00 pm
Previous DPM (DPMt-1)	Continuous	DPM measured in the preceding hour.
Environmental variables		
Wind speed (Wspd)	Continuous	Averaged over the 10 min directly preceding each hour, measured in knots
Wind direction (Wdir)	Continuous, cyclic	Averaged over the 10 min directly preceding each hour, measured in degrees
T-POD position (TPOD)	Factor, 3 levels	Inner (1), mid (2) or outer (3) harbour position
Tide (tide)	Continuous, cyclic	Hours since last high tide

Table 4
T-POD deployment and detections. 'Detection positive days' is the number of days on which at least one dolphin click was detected. DPM = detection positive minutes; SE = standard error.

T-POD	Days deployed	Detection positive days	Mean DPM per day (SE)
Inner	92	82	12.83 (1.52)
Mid	92	91	29.47 (1.97)
Outer	41	41	55.27 (6.40)

Christmas-New Year during which no pile-driving occurred. The outer T-POD, while in place, had consistently more detections of Hector's dolphins than the other two (Table 4).

3.1. DPM per day

The model which included the piling-related variable PPM was the top model, and had a higher Akaike weight than those that did not (Table 5). The effect of many of the variables differed by location (Table 6).

An increase in PPM per day led to a decrease in DPM per day at the inner and outer T-PODs, and an increase in DPM at the mid T-POD (Fig. 2). The variable SEL was not present in the top models.

DPM per day decreased with increasing wind speed at the inner and mid T-POD (Fig. 2). At the inner T-POD, increased detections were seen during westerly winds, and decreased detections during easterly winds (Fig. 2).

3.2. DPM per hour

The six highest rated models, by Akaike weight, all contained three piling-related variables (TSP, SEL and Dur), the 7th and lowest rated model contained two piling-related variables. Relationships among variables were more complex in the DPM per hour dataset, for which top models included all variables tested, as well as the interaction between time-since-piling and duration-of-piling (Tables 7 and 8).

The lowest detection rate at the inner T-POD was seen within 2000 mins (33 h) after piling (Fig. 3). After this point the rate steadily increased and levelled off around 5000 mins (83 h). DPM per hour decreased with increasing SEL at all T-POD locations (Fig. 3). An increase in duration of pile-driving led to a decrease in detection rate, up to a duration of about 150 mins (Fig. 4). The interaction between time-since-piling (TSP) and duration-of-piling (Dur), at the inner T-POD, showed decreasing detection rates within the first 2000 mins (33 h) of piling (Fig. 5). Detection rates returned to the level of the previous hour (set at 1.1 DPMs) after 3000–3500 min (50–58 h) (Fig. 5). The first maximum following the minimum occurred at 5000 min. Therefore, this time most likely represents the time to recovery, see Brandt et al. (2011). There were more subtle effects with duration. For short duration events (< 100 min) the lowest DPM per hour was seen directly after piling, and was lower than that of the previous hour (Fig. 5). For longer duration events, however, the lowest DPM was seen around 2000 mins (33 h) after piling, as shown by the 0.4 contour (Fig. 5). Beyond 5000 mins after piling, DPM per hour decreased with time.

At the inner T-POD, detection rates were highest around 5–6 am and the lowest around 11–12 pm, with another peak in detections at 5–6 pm (Fig. 3). At the mid T-POD the highest rate was seen around 4–5 pm, and the lowest around 5–6 am (Fig. 3). At the inner T-POD, highest detection rates were seen around 100 mins after high tide (Fig. 3). At the mid T-POD, detection rates were highest around low tide, and at the outer T-POD around high tide (Fig. 3). Wind direction had the overall effect of increased DPM per hour during northerly winds and decreased during southerly winds (Fig. 4). Detection rates tended to decrease with increasing wind speed (Fig. 4).

Table 6
Index of relative importance (IRI), estimated degrees of freedom (edf) and significance (*p*-value) for the parametric (first 3 rows) and smoothed terms in the top model in the DPM per day dataset. Bold terms are significant at the 5% level. *The first three rows of 'edf' are coefficient estimates for the parametric terms.

Term	IRI	edf	p-value
Intercept	**1**	**2.71***	**< 2e-16**
TPOD2	**1**	**0.57***	**5.86e-4**
TPOD3	**1**	**1.07***	**1.32e-6**
ti(DPMt-1):TPOD1	**1**	**2.56**	**0.001**
ti(DPMt-1):TPOD2	**1**	**1.00**	**0.008**
ti(DPMt-1):TPOD3	1	1.00	0.174
ti(Wspd):TPOD1	**1**	**1.00**	**0.006**
ti(Wspd):TPOD2	**1**	**1.00**	**0.012**
ti(Wspd):TPOD3	1	1.00	0.446
ti(Wdir):TPOD1	**0.9**	**1.78**	**0.006**
ti(Wdir):TPOD2	0.9	0.00	0.387
ti(Wdir):TPOD3	0.9	1.17	0.059
ti(PPM):TPOD1	0.49	1.00	0.062
ti(PPM):TPOD2	0.49	1.00	0.104
ti(PPM):TPOD3	0.49	1.00	0.486

4. Discussion

4.1. Pile-driving and the effect on dolphin detections

Multi-model inference revealed that the top models contained at least one piling-related variable, indicating that pile-driving influenced detection rates of Hector's dolphins in Lyttelton Harbour. Considering that several studies of harbour porpoise have shown that animal density is correlated to the number of acoustic detections (Marques et al., 2009; Sveegaard et al., 2011; Kyhn et al., 2012; Dähne et al., 2013), we propose that this is the most parsimonious explanation for differences in detection rates of Hector's dolphins also. DPM per day decreased at the inner T-POD, as piling (PPM) increased, while it increased at the mid-harbour T-POD. The mid harbour location is further from the piling activity, and is partially shielded by Sticking Point (Fig. 1). Average broadband sound levels were 14 dB lower at the mid-harbour T-POD (Table 1, see Leunissen and Dawson, 2018 for more detail). Taken together, these data suggest that dolphins displaced from the inner harbour moved towards the mid harbour area, increasing the chance they were detected by the mid T-POD. This effect was also observed visually in a study of impact of pile-driving from offshore wind farm construction on harbour porpoise (Dähne et al., 2013). The lack of strong trends for piling related variables at the outer T-POD indicates this detector was outside the zone of impact and, thus, provides an outer boundary.

Table 5
Results of model selection for GAMs with DPM per day as the response variable. Only models within 6 AICc points of the top model are shown. Rank is based on AICc, 'Wt' is the Akaike weight of the model, '% DE' is the percentage deviance explained by the model, R^2 is the adjusted r-squared value, and the 'Model' column shows the model structure. Terms enclosed by 's()' are smoothed variables, and by 'ti()' are smoothed seperately for each T-POD location.

Rank	Model	df	AICc	ΔAICc	Wt	% DE	R^2
1	T-POD + ti(DPMt-1) + ti(Wspd) + ti(Wdir) + ti(PPM)	18.9	1746.92	0	0.49	44.2	0.48
2	T-POD + ti(DPMt-1) + ti(Wspd) + ti(Wdir)	15.6	1747.25	0.33	0.41	42.2	0.48
3	T-POD + ti(DPMt-1) + ti(Wspd)	12	1750.06	3.13	0.1	39.3	0.443

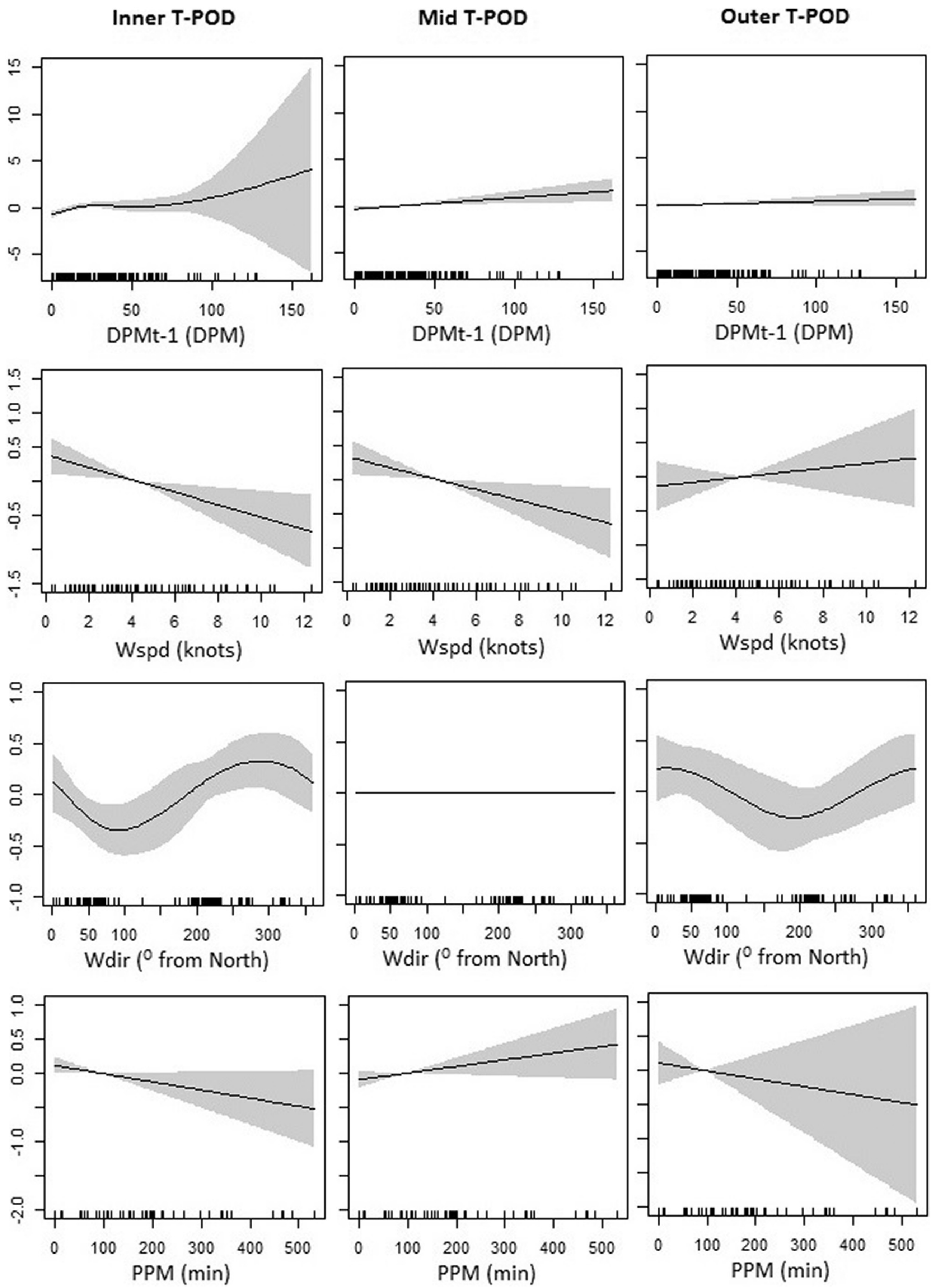

Fig. 2. The predicted smoothing functions for each explanatory variable, from the highest ranked model in which it appears, and its effect on DPM per day (y-axis) with shaded 95% confidence intervals. The ticks along the bottom edge of the plot indicate the values found in the measured data for that variable.

Table 7
Results of model selection for GAMs with DPM per hour as the response variable. Only models within 6 AICc points of the top model are shown. Rank is based on AICc, 'Wt' is the Akaike weight of the model, '% DE' is the percentage deviance explained by the model, R^2 is the adjusted r-squared value, and the 'Model' column shows the model structure. Terms enclosed by 's()' are smoothed variables, and by 'ti()' are smoothed seperately for each T-POD location, except the term 'ti (TSP,Dur)' which is an interaction between the 2 variables.

Rank	Model	df	AICc	Δ	Wt	% DE	R^2 (adj.)
1	ti(DPMt-1) + TPOD + ti(Hour) + ti(TSP) + ti(SEL) + ti(tide) + ti(TSP,Dur) + ti(Wdir) + s(Dur)	46.4	10,491.1	0	0.46	19.3	0.152
2	ti(DPMt-1) + TPOD + ti(Hour) + ti(TSP) + ti(SEL) + ti(tide) + ti(TSP,Dur) + ti(Wdir)	43.05	10,492.2	1.1	0.27	19.1	0.152
3	ti(DPMt-1) + TPOD + ti(Hour) + ti(TSP) + ti(SEL) + ti(tide) + ti(TSP,Dur) + ti(Dur)	41.66	10,494.6	3.5	0.08	19.1	0.148
4	ti(DPMt-1) + TPOD + ti(Hour) + ti(TSP) + ti(SEL) + ti(tide) + ti(TSP,Dur) + ti(Wspd)	43.99	10,494.8	3.7	0.07	18.9	0.148
5	ti(DPMt-1) + TPOD + ti(Hour) + ti(TSP) + ti(SEL) + ti(tide) + ti(TSP,Dur)	40.8	10,495.6	4.5	0.05	18.8	0.148
6	ti(DPMt-1) + TPOD + ti(Hour) + ti(TSP) + ti(SEL) + ti(tide) + ti(Wdir) + s(Dur)	42.75	10,496.1	5.0	0.04	18.9	0.158
7	ti(DPMt-1) + TPOD + ti(Hour) + ti(TSP) + ti(SEL) + ti(tide) + ti(Wdir)	39.54	10,496.4	5.3	0.03	18.7	0.157

Table 8
Index of relative importance (IRI), estimated degrees of freedom (edf) and significance (p-value) of each term in the top model (except for s(Wspd) - values are from 4th best model) for the parametric (first 3 rows) and smoothed terms in the DPM per hour dataset. Bold terms are significant at the 5% level. *The first three rows of 'edf' are coefficient estimates for the parametric terms.

Term	IRI	edf	p-value
Intercept	**1**	**−0.84***	**< 2e-16**
TPOD2	**1**	**0.97***	**< 2e-16**
TPOD3	**1**	**1.28***	**< 2e-16**
ti(DPMt-1):TPOD1	**1**	**3.01**	**< 2e-16**
ti(DPMt-1):TPOD2	**1**	**2.31**	**9.74e-08**
ti(DPMt-1):TPOD3	**1**	**2.26**	**1.54e-04**
ti(TSP):TPOD1	**1**	**3.57**	**2.58e-05**
ti(TSP):TPOD2	1	1.00	0.132
ti(TSP):TPOD3	1	1.75	0.355
ti(Hour):TPOD1	**1**	**2.82**	**8.18e-05**
ti(Hour):TPOD2	**1**	**1.98**	**0.001**
ti(Hour):TPOD3	1	0.00	0.643
ti(SEL):TPOD1	**1**	**2.48**	**0.034**
ti(SEL):TPOD2	1	1.00	0.129
ti(SEL):TPOD3	1	1.46	0.098
ti(tide):TPOD1	**1**	**1.66**	**0.019**
ti(tide):TPOD2	1	0.96	0.157
ti(tide):TPOD3	**1**	**1.86**	**0.005**
ti(TSP,Dur)	**0.93**	**3.04**	**0.045**
s(Wdir)	**0.8**	**1.72**	**0.013**
s(Dur)	0.57	2.96	0.185
s(Wspd)	0.08	1.00	0.057

This is reinforced by the low noise contours at this location in Leunissen and Dawson (2018).

The greater temporal resolution of the DPM per hour response variable supported a more nuanced analysis, indicating that time-since-piling, piling SEL and the interaction of time-since-piling and duration were significant influences. Here also, responses were often location specific. DPM per hour at the inner harbour T-POD decreased significantly with increasing SEL (Fig. 3) indicating that it was not only the presence of pile-driving but also its intensity that led to avoidance reactions. This is probably why studies assessing the impact of windfarm construction on harbour porpoise see avoidance reactions at much larger distances (around 20 km; Tougaard et al., 2009; Brandt et al., 2011; Dähne et al., 2013). Pile-driving for windfarms involves much larger piles (around 2.4–4 m diameter, compared to 0.61–0.71 m in Lyttelton) and correspondingly heavier pile drivers, leading to much higher sound source levels (Fricke and Rolfes, 2015). Also, the harder substrate found in these offshore locations (sand/gravel, compared to the fluid mud layer in Lyttelton) allows the sound to propagate further (due to increased reflection from the bottom surface; Jensen et al., 2011). This effect on propagation leads to an increase in range at which the sound can be heard.

4.2. Duration of impact

Analysis of DPM per hour suggested that the decreasing trend in detection rate following a pile-driving event lasted around 33 h. Detection rate restored to the level of the hour prior to exposure after 83 h. This gradual increase in detections after 33 h probably reflected the gradual return of dolphins to the inner harbour following a pile-driving event. Levelling-off of the trend in detection rate with time-since-piling (as in Brandt et al., 2011) indicates that the previous piling event no longer has an effect on detection rate. This was observed in the current study at 83 h. The modelled decline in DPM (see Figs. 3 and 5) after that point was not well supported by data (only during the Christmas/New year break did time-since-piling exceed 90 h). The maximum duration of effect on detections (83 h) is comparable to, though slightly longer than, the longest duration of effect estimated for the impact of pile-driving on harbour porpoise (72 h; Brandt et al., 2011). It is interesting that the lowest detection rate did not occur immediately after pile-driving, but rather 33 h later. This seems counterintuitive and is not observed in other studies (e.g. Tougaard et al., 2009; Brandt et al., 2011), but could have been driven by a need to stay in the area for foraging opportunities, for example. Another reason for this delayed minimum could be due to lower SEL in this study. Louder sounds are more likely to result in an immediate impact, while quieter sounds could be tolerated for longer before a threshold is reached.

DPM per hour decreased with duration of the previous pile-driving event up to a duration of 150 mins, although the effect was not strong. There was however an important interaction between time-since-piling and duration of the previous piling event. For long duration piling events, the decrease in DPM per hour persisted for longer after piling had finished.

4.3. Influence of other factors

T-POD location was the most significant influence on detection rate of Hector's dolphins in Lyttelton Harbour (Table 8). Similar fine-scale variation in spatial distribution of Hector's dolphin has previously been revealed by other acoustic (e.g. Dawson et al., 2013), and visual surveys (e.g. Brough et al., 2018). Decreased hourly detections at the inner T-POD between 7 am and 4 pm could be due to disturbance by higher levels of vessel traffic near the wharf and construction activity during working hours (e.g. increased swimming speed in killer whales with increased boat traffic, following a diurnal pattern (Kruse, 1998)). Another explanation could be diel movements of prey (as observed with harbour porpoise; Todd et al., 2009). The changes in detections in response to time of day are in addition to the changes following pile-driving events (accounted for by the model structure). Since we were unable to acquire true control data, however, it cannot be concluded that Hector's dolphin detections would follow the same daily trend outside the monitoring period, with no construction activities taking place. Diurnal variation in Hector's dolphin habitat use has previously been observed in Porpoise Bay (Bejder and Dawson, 2001) and Akaroa

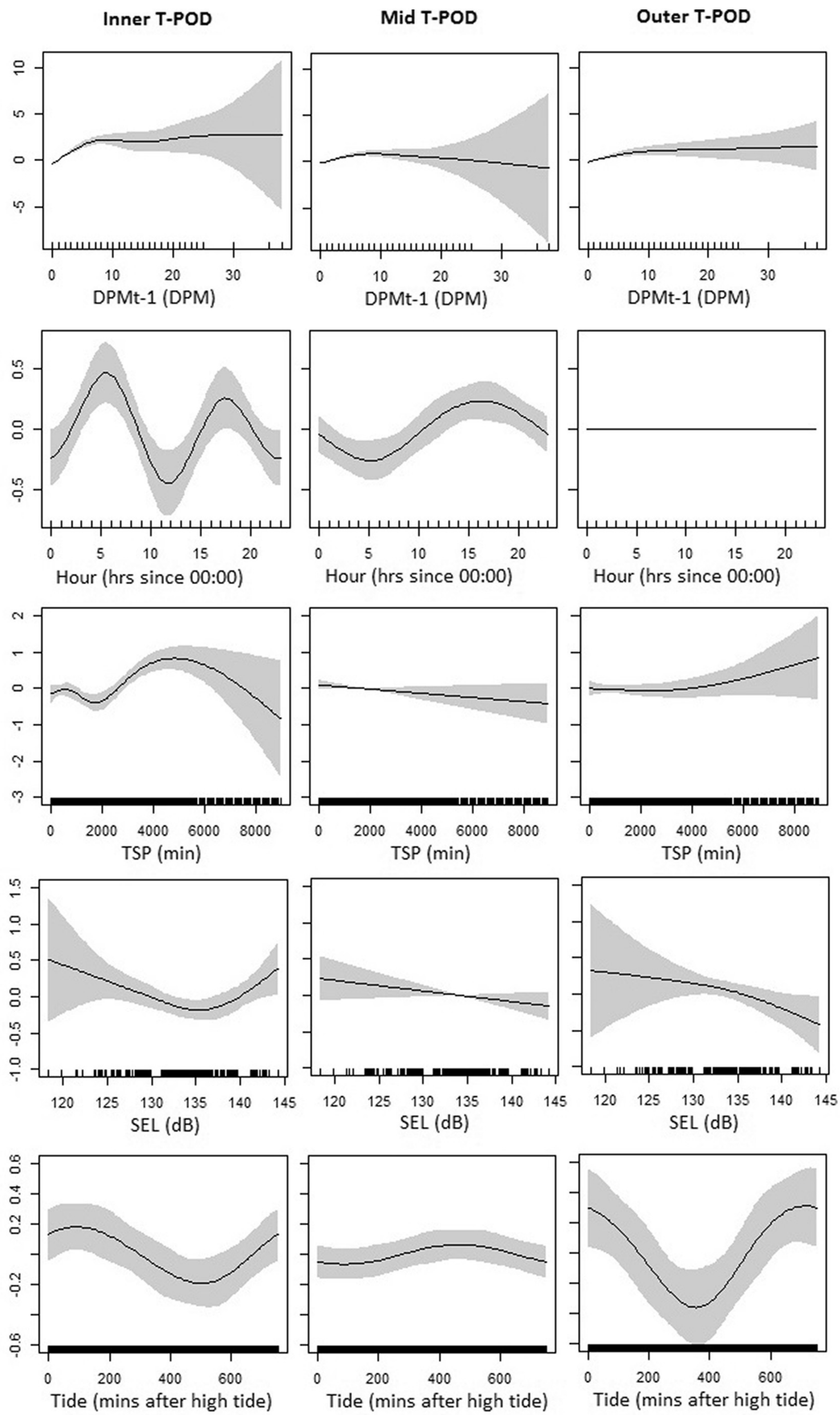

Fig. 3. The predicted smoothing functions for each explanatory variable and its effect on DPM per hour (y-axis) with shaded 95% confidence intervals. The ticks along the bottom edge of the plot indicate the values found in the measured data for that variable.

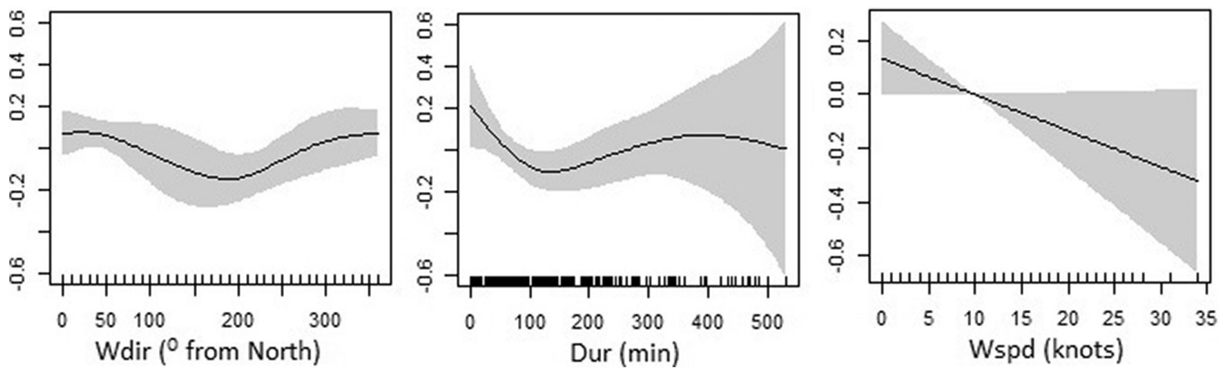

Fig. 4. The predicted smoothing functions for the explanatory variable and its effect on DPM per hour at all T-POD locations (y-axis) with shaded 95% confidence intervals. The ticks along the bottom edge of the plot indicate the values found in the measured data for that variable.

Harbour (Dawson et al., 2013), but does not follow the same trend as observed in this study.

State of the tide also had a significant effect on Hector's dolphin distribution in nearby Akaroa Harbour (Dawson et al., 2013). Furthermore, detection rates of bottlenose dolphins on the coast of Scotland (Mendes et al., 2002), and harbour porpoise in the Bay of Fundy (Johnston et al., 2005) were correlated with tidal state. A possible driver for the variation in dolphin distribution is the tidally mediated movement of prey species. For example, yellow-eyed mullet (*Aldrichetta forsteri*), identified as a prey species from Hector's dolphin stomach contents (Miller et al., 2012), was most often caught at night time low tides in Manukau Harbour, northern New Zealand (Morrison et al., 2002).

At least at the inner and middle T-POD locations, more dolphin detections were made at lower wind speeds. This was possibly due to higher attenuation of click sounds during high wind speeds in shallow water, caused by the increased amount of air bubbles in the water and less reflection at the ruffled water surface (Norton and Novarini, 1996). In contrast, Brandt et al. (2016) observed the opposite effect of wind on detections of harbour porpoise. This effect was determined to be due to the increased propagation of piling noise at lower wind speeds, leading to lower detection rates. In addition, more noise clicks were recorded at higher wind speeds due to increased levels of ambient noise giving false-positive detections (Brandt et al., 2016).

4.4. Temporary threshold shift (TTS) in hearing

This study showed that pile-driving noise clearly influenced Hector's dolphin distribution. Another important impact from the noise is increased risk of hearing damage, particularly close to the piling activity. Leunissen and Dawson (2018) calculated zones of potential impact in Lyttelton Harbour based on hearing studies of harbour porpoise (Kastelein et al., 2013a; Kastelein et al., 2013b; Kastelein et al., 2015). These zones depend on the length of time they spend near the pile-driving. While these zones did not cover very large areas, Hector's dolphins may tolerate noise at levels which could induce TTS if there was a sufficient reward for doing so. Hector's dolphins have been observed inside the zones where they are at risk of TTS. We visually observed dolphins (near our close-range sound recorder moored about 370 m from the piling activity) and, thus, have many recordings of their clicks (up to 10 consecutive dolphin positive minutes) during pile-driving events. Masking of environmental sounds is highly likely in the inner harbour. The spatial extent of these impacts into the outer harbour was heavily reduced due to the shielding effect of the breakwater at Sticking Point (Leunissen and Dawson, 2018).

The sensitivity of Hector's dolphin hearing has not yet been tested, so the TTS calculations by Leunissen and Dawson (2018) assumed that it is similar to that of harbour porpoise. Two lines of evidence suggest that Hector's dolphin hearing might be significantly more sensitive. First, the source level of Hector's dolphin echolocation clicks is much lower than that of harbour porpoises (Kyhn et al., 2009), implying that to serve the same function the receiver system should be more sensitive. Second, we detected behavioural change in Hector's dolphins at SELs lower than those which have been observed to modify behaviour of harbour porpoise (Tougaard et al., 2009; Bailey et al., 2010; Brandt et al., 2011; Dähne et al., 2013; Kastelein et al., 2013b).

In summary, pile-driving noise was associated with a decrease in detection rate of Hectors' dolphins at the inner T-POD, with an increase

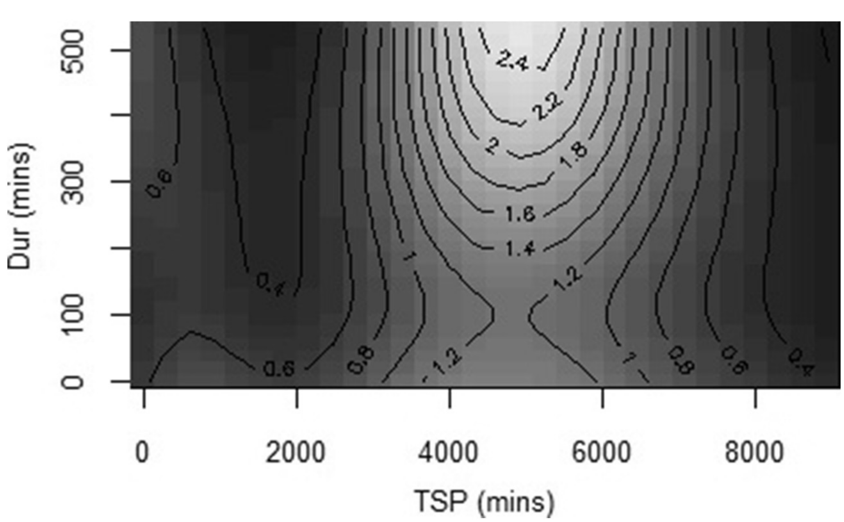

Fig. 5. Interaction between time-since-piling (TSP) and Duration-of-piling (Dur) calculated in the top model, with contours showing the predicted DPM per hour at the inner TPOD when the other variables are fixed as follows: "Hour" = 16 (4 pm), "Wdir" = 50° from North, "tide" = 100 mins after high tide, "SEL" = 134 dB, "DPMt-1" = 1.1 mins.

in detections per day seen at the mid T-POD. The most parsimonious explanation is that this was driven by dolphins moving from the inner harbour to the mid harbour when pile-driving was underway. Reduced density of dolphins near the inner T-POD was also implied by decreasing detection rates following a bout of piling, restoring to pre-piling levels after 50–83 h. Intensity of piling also affected detection rate, with fewer detections in the inner harbour on days with longer duration piling activity, and fewer detections per hour after longer and louder piling events. Pile-driving has also been shown to introduce a risk of TTS (Leunissen and Dawson, 2018).

We have demonstrated that pile-driving had an effect on Hector's dolphins's use of Lyttelton Harbour. While the population level effect is uncertain, the extra energy expenditure from area abandonment and reduced foraging opportunities are potentially very important in the context of the endangered status of this species, and in addition to the other threats it faces. It is essential that future research strives to quantify the population level impacts. In the meantime, society should take a precautionary approach to such impacts, taking whatever means possible to reduce the likelihood of detrimental change.

There are options to mitigate the noise-related effects of pile-driving. For example, bubble curtains can significantly reduce the noise radiated into the water column (Lucke et al., 2011; Nehls et al., 2016; Tsouvalas and Metrikine, 2016) particularly when confined (e.g. Buehler et al., 2015). For Lyttelton Harbour, however, significant re-suspension of sediment could breach a condition of the Coastal Permit, and therefore makes bubble curtains an unlikely noise-mitigation option for future construction work. A strategy for reducing noise pollution could be to employ screw-piling technology, rather than impact pile-driving, which produces significantly less underwater noise (Saleem, 2011). Since Hector's dolphins are generally found closer inshore during the summer (Rayment et al., 2010; Brough et al., 2014, 2018), restricting piling to winter time would also likely reduce its impact.

Declarations of interest

None.

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Appendix A

Temporal autocorrelation

Two methods were used to reduce temporal auto-correlation in both datasets, tested using the *acf* function in R. The use of the DPMt-1 variable in the models (Tables 2 and 3) was much more effective in reducing temporal auto-correlation in model residuals than using a corAR1 correlation structure, in both datasets (Figs. A.1 and A.2).

DPM per hour

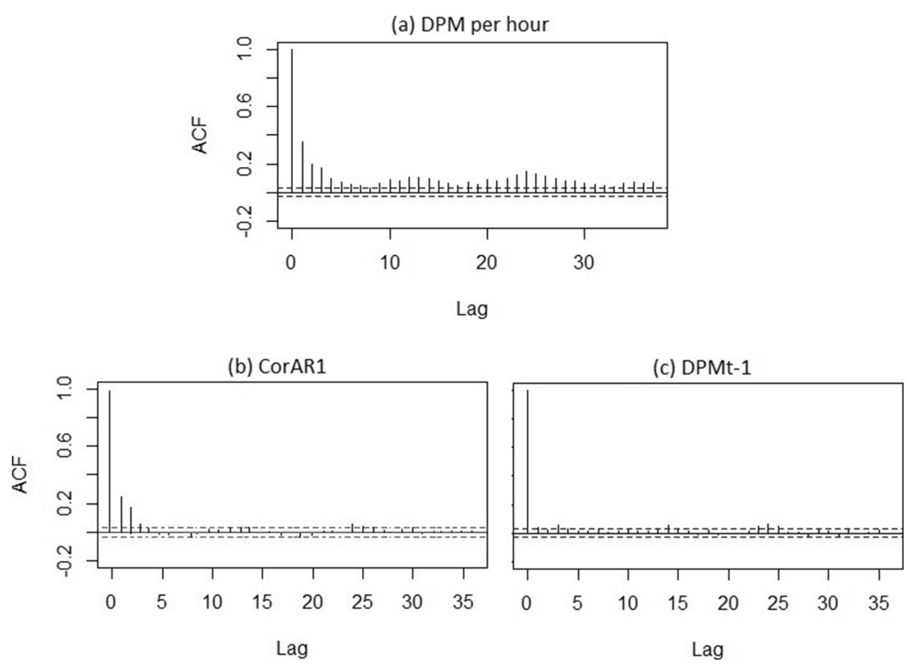

Fig. A.1. (a): Temporal autocorrelation of the DPM per hour variable; (b): Temporal autocorrelation of the residuals of the top model, with the corAR1 correlation structure, of DPM per hour; (c): Temporal autocorrelation of the residuals of the top model, with the DPMt-1 variable, of DPM per hour. Horizontal dotted lines indicate the 95% confidence interval of white noise of this series.

DPM per day

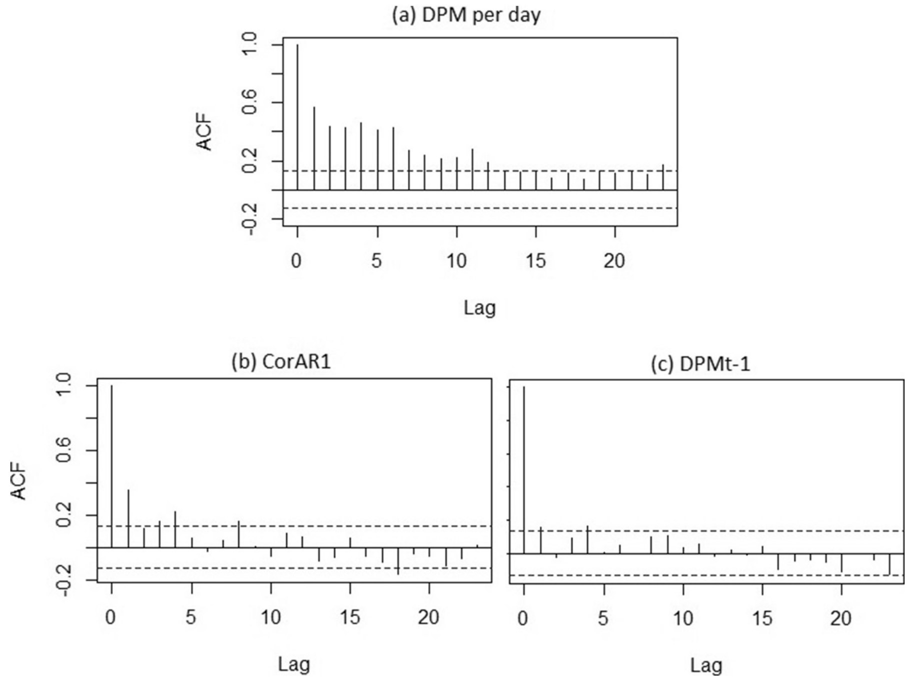

Fig. A.2. (a): Temporal autocorrelation of the DPM per day variable; (b): Temporal autocorrelation of the residuals of the top model, with the corAR1 correlation structure, of DPM per day; (c): Temporal autocorrelation of the residuals of the top model, with the DPMt-1 variable, of DPM per day. Horizontal dotted lines indicate the 95% confidence interval of white noise of this series.

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