Contents lists available at ScienceDirect

Regional Studies in Marine Science

journal homepage: www.elsevier.com/locate/rsma

Distribution patterns of blue whale (*Balaenoptera musculus*) and shipping off southern Sri Lanka

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HIGHLIGHTS

- High densities of blue whales overlap with shipping lanes, resulting in severe ship strike risk.
- Blue whales are regularly reported struck by ships off the southern coast of Sri Lanka.
- Results suggest that risks could be reduced by 95% if shipping were to transit 15 nm further offshore.

ARTICLE INFO

Article history:
Received 21 January 2015
Received in revised form
28 July 2015
Accepted 4 August 2015
Available online xxxx

Keywords:
Blue whale
Ship strike
Sri Lanka
AIS
Collision risk

ABSTRACT

Surveys were conducted off the southern coast of Sri Lanka in 2014 and 2015 to investigate the distribution patterns of blue whales (*Balaenoptera musculus spp.*) in relation to current shipping lanes, and further offshore. There have been several reported ship strikes of blue whales in this area and the IWC Scientific Committee has recognised the potential for ship strikes to have population level impacts on blue whales in the northern Indian Ocean. A total of 3268 km of visual survey effort was conducted on 35 survey days along north–south transects between 5°28′N and 5°53′N. These data were used to model patterns of whale density. The highest densities of blue whales were observed in the current shipping lanes, peaking at an average of 0.1 individuals km^{-2} along the westbound shipping lane. Automatic Identification System transmissions received by satellite were used to estimate shipping density. Between 80°30′E and 81°E, the peak mean shipping density in the westbound lane of the Traffic Separation Scheme was 1090 km^{-1} $year^{-1}$ and in the eastbound lane 810 km^{-1} $year^{-1}$. These high densities of whales combined with one of the busiest shipping routes in the world suggest a severe risk of ship strikes. Previous data on blue whale distribution and coastal upwellings indicate consistent and predictable patterns of whale distribution, suggesting there is considerable potential for effective measures to keep ships and whales apart. For example, data from this study would suggest risk could be reduced by 95% if shipping were to transit 15 nm further south than currently.

1. Introduction

Wherever vessels and whales coincide, there is a risk of collisions. Consistently high densities of blue whales (*Balaenoptera musculus spp.*) are found off southern Sri Lanka in one of the busiest shipping routes in the world, resulting in a particularly high risk. Ship strikes are recognised as an issue for the Northern Indian Ocean blue whale population (de Vos et al., 2013a). Ilangakoon (2012) reports an increase in blue whale strandings off the south and west coast of Sri Lanka since 2010, with nine occurring between January 2010 and April 2012. Of these, several showed signs of blunt force trauma and propeller lesions. An analysis of 15 whale

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http://dx.doi.org/10.1016/j.rsma.2015.08.002
2352-4855/

Please cite this article in press as: Priyadarshana, T., et al., Distribution patterns of blue whale (*Balaenoptera musculus*) and shipping off southern Sri Lanka. Regional Studies in Marine Science (2015), http://dx.doi.org/10.1016/j.rsma.2015.08.002

mortalities attributed to ship strikes around Sri Lanka between 2010 and 2012 found that 11 of these were blue whales. The majority of these were found as stranded carcasses on the south coast (Nanayakkara, R., pers. comm.). Between January and May 2014, four blue whale deaths were reported along the southern coast (Randage et al., 2014). During the NE monsoon, winds are cross or offshore with strong, westward cross-shore surface currents making it unlikely that carcasses of whales killed in the shipping lanes would strand during these months. It can be assumed that only a very small proportion of collisions are reported or result in a whale stranding; for example, off the coast of California, the estimated reporting rate for ship strike blue whale deaths is between 0.4% and 4.2% (Monnahan et al., 2015). Even so, the number of reported ship strikes since 2010 is higher than for any other large whale population globally that we are aware of. In 2012, the Scientific Committee of the International Whaling Commission (IWC) drew attention to the urgent need for long-term monitoring of the blue whale population in Sri Lankan waters and elsewhere in the northern Indian Ocean because of the potential for population impacts from ship strikes (IWC, 2013).

A growing awareness of the ship strike problem at a global level, and potential for measures to reduce risk have resulted in a number of initiatives through the International Maritime Organization (IMO). In 2009, IMO issued a guidance document for minimising the risk of ship strikes with cetaceans (IMO, 2009). Other measures taken through IMO were reviewed by Silber et al. (2012). More recently, specific measures to reduce risk to blue whales were proposed by the USA and in December 2012, IMO adopted changes to the shipping lane in the Santa Barbara Channel, California, USA (IMO, 2012).

Blue whales are found in Sri Lankan waters all year round (Ilangakoon and Sathasivam, 2012; Randage et al., 2014). Sightings rates vary between seasons but seasonal changes are not well understood because effort and sighting conditions also vary considerably between seasons. Martenstyn (2013) reports that blue whales are widely distributed in Sri Lankan waters, occurring in pelagic waters as well as near the continental shelf break and on the continental shelf. The status of the Northern Indian Ocean population of blue whales is not known, but at least 1294 blue whales were taken from the Arabian Sea in illegal catches by the former Soviet Union between 1963 and 1966 (Mikhalev, 2000). Small numbers of catches were also taken offshore of southern Sri Lanka and between Sri Lanka and the Maldives (Branch et al., 2007). Acoustically, blue whales off Sri Lanka have a distinctive call type (Alling and Payne, 1991) which has also been recorded off Chagos (Stafford et al., 2011) and as far south as Crozet (Samaran et al., 2010). Information on distribution patterns and probable movements of blue whales in the northern Indian Ocean is reviewed in Branch et al. (2007) and Anderson et al. (2012).

Data on patterns of shipping can be derived from Automatic Identification System (AIS) signals received from satellites. All vessels of greater than 300GT are required to transmit AIS signals which then provide reliable data on shipping density (Leaper and Panigada, 2011). However, availability of AIS data to estimate shipping density is relatively recent. To investigate earlier patterns of shipping, Tournadre (2014) used altimeter data to compare densities in 1992 and 2012. Results showed that in the Indian Ocean, which has some of the world's busiest lanes, there was a 300% increase in shipping between the average from 1993 to 2002 and the average from 2003 to 2012. The risk of collision with blue whales would be expected to have increased similarly. This increase is larger than other areas such as the Atlantic or Pacific.

The aim of this study was to investigate patterns of blue whale distribution in relation to shipping in a small area off the southern tip of Sri Lanka to provide baseline data that could be used to reduce ship strike risk and provide information on population status. In addition to the collision risk to the whales, there is a growing whalewatching industry which also operates in this area of high density shipping, raising concerns over maritime safety. Data were also collected on the distribution patterns of small coastal fishing vessels for which there are safety concerns. Although there are considerable data on whale distribution from whalewatching vessels, these data are limited to the areas closest to the port of Mirissa in which most whalewatching operations are based. There is thus a need for survey data covering a wider area and particularly further offshore.

1.1. Previous whale data

A key issue in evaluating ship strike risk is to understand the inter- and intra-annual variability in whale distribution and in particular the distribution patterns of high density areas of whales. The survey results presented here need to be considered in the context of longer-term datasets on distribution patterns.

Blue whale distribution patterns are often associated with bathymetry. Off the east coast of Sri Lanka, Alling et al. (1991) reported seeing most blue whales around the 200 m contour with none seen in the deepest water surveyed furthest offshore. These authors also concluded that Sri Lankan waters were an important feeding area based on depth sounder traces of repeated dives into dense patches of presumed prey and frequent observations of defecation at the surface. Blue whales off the south coast are also frequently seen to defecate and show the same high proportion of dives initiated with a fluke up. This suggests the south coast is also an important feeding area. Martenstyn (2013) notes concentrations of sightings recorded around submarine canyons where whales are thought to aggregate for feeding.

Data have been collected on all whale sightings made by the whalewatching company *Raja and the Whales* since 2009. These sightings locations showed little differences in location between years (Randage et al., 2014). Ilangakoon (2012) also presented some sightings data in a similar area from 2008/09 and from 2011. The survey tracks are not shown, but in 2008 and 2009 whales were seen inshore of the 1000 m contour, whereas in 2011 they were seen within the shipping lanes. The more inshore distribution in 2008/09 does indicate that the whale distribution may change in response to environmental conditions. Martenstyn (2013) also lists over 100 sighting locations from the Sri Lanka navy vessel *Princess of Lanka* operating whalewatching trips out of Galle between 12/11/2011 and 19/02/2013. The furthest south of any of these sightings was 5° 39.745′N which corresponds to the southern edge of the eastbound shipping lane. However, it is not clear if the vessel ever searched any further south than this. These show very similar locations to the data from *Raja and the Whales*, suggesting little change in distribution within the whalewatching areas for 2011–2014. de Vos et al. (2014) describe differences in distribution and encounter rates between 2011 and 2012 from the inshore waters north of 5° 42′N. Sightings rates closest inshore were lower in 2011 which was attributed to high fresh water run-off. Although inter-annual changes in distribution patterns were detected over the period 2009–2012, none of the sightings of blue whales from that study was south of the current Traffic Separation Scheme (TSS). It seems unlikely that effects of freshwater run-off would extend much further offshore than the area covered by the surveys of de Vos et al. (2014).

2. Methods

2.1. Survey design and analysis

For this study we defined a survey area of approximately 50 km from north to south and 150 km from east to west (Fig. 1). This was

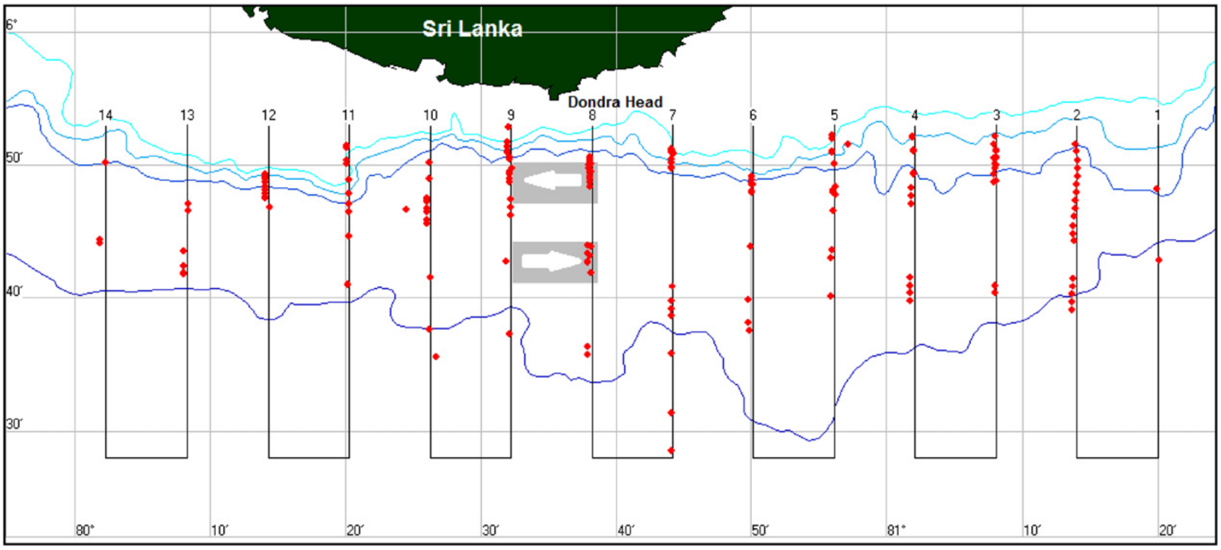

Fig. 1. Locations of blue whale sightings from survey transects in 2014 and 2015. Grey boxes are current shipping lanes (arrows show direction of travel) associated with the Traffic Separation Scheme off Dondra Head. Depth contours are (from north to south) 200, 500, 1000, 3000 m.

based on a combination of operational constraints and the need to survey as far offshore of the current shipping lanes as possible.

Between February 2014 and April 2015, 29 days of visual and acoustic line transect survey were conducted from *Raja and the Whales*, a 13 m converted deep-sea fishing vessel and 9 days from *Mir*, a 35 m auxiliary powered sailing research vessel. Survey dates are shown in Table 1. There was an initial block of effort between February and April 2014 followed by individual survey days in July 2014, October 2014, December 2014 and January 2015. These were followed by a block of surveys in March and April 2015. Of these all were within inter-monsoon or NE monsoon periods except the survey on 16 July 2014. This single survey was not included in the spatial modelling analysis because the different oceanographic conditions might be expected to result in different factors influencing whale density. Fourteen transect lines were designed to cover the area of the shipping lanes and the surrounding areas, both inshore-offshore and east–west (Fig. 1). Transects ran north to south, perpendicular to the shipping lanes (which run east to west). Transects started at 5° 53′N, 3 nm north of the shipping lane, and ended at 5° 28′N. Thus the survey box covered the main shipping lane and an area 15 nm further offshore to the south.

Transects from *Raja and the Whales* were conducted at a survey speed of approximately 6 knots. Observations were carried out from the upper forward deck of the vessel with a platform height of 2.75 m. Two observers using naked eye and Opticron 7 × 15 binoculars searched a 90° sector either side of the vessel, and recorded sightings data for all marine fauna detected. Distances and angles to sightings were measured using binocular compass and reticles. Where conditions did not allow the use of reticles, an estimate of distance was made. Observers used reticle readings to small vessels to train naked eye estimates but no systematic experiments were conducted to estimate distance errors to whale sightings. Sightings and environmental data, were recorded using Logger 2010 (Gillespie et al., 2011). No data were collected in conditions above Beaufort sea state 5.

In addition to data on whale distribution, data on other vessel traffic (including small fishing vessels) were recorded. The distance to each vessel when it came abeam was recorded along with the type of vessel.

Although the main aim of the survey was to examine relative whale distribution patterns, absolute estimates of whale abundance are valuable for estimating ship strike risk and for comparison with other areas. Programme Distance (Thomas et al., 2010) was used to estimate strip widths to allow for density estimation. However, no attempt was made to estimate the absolute detection probability on the trackline ($g(0)$), which was assumed to be 1. This is a common assumption for blue whale surveys and where $g(0)$ has been estimated in other studies it has been close to 1 (Calambokidis and Barlow, 2004). In addition to Distance analysis, transects were divided into 1 km segments for the purposes of spatial modelling. The results presented here are for a simple spatial Generalized Additive Model (GAM) including possible covariates of latitude, longitude, depth, slope, Beaufort sea state, and sightability. Sightability was a subjective category on a scale of one to five of how good the observers judged the conditions for seeing blue whales to be based on all factors. The response variable was the number of whales sighted in each 1 km segment of survey track. Modelling was performed using the mgcv package in R (Wood, 2006; R Development Core Team, 2008). Depth data were taken from the Gebco_08 grid (version 20100927 www.gebco.net) at 30 arc-second (approximately 925 m spacing). Since depth contours run predominantly east–west across the survey area, slope was defined in just a north–south direction as the angle in a vertical plane between the closest two measurement points. The east–west nature of the depth contours also results in latitude and depth being effectively collinear. Alternative models were evaluated using either latitude or depth but not both. GAMs were fitted based on a Tweedie distribution to allow for the over-dispersion and disproportionate number of segments with zero sightings compared to Poisson (Miller et al., 2013). The percentage of explained deviance was used as an indication of model fit.

2.2. Methods for estimating shipping density

Satellite-received AIS data were provided by MarineTraffic.com for the area 5°N–6.5°N and 79.5°E–82°E. Data were collected over a 320 day period from 03/07/2013 to 17/05/2014. Satellite coverage was not continuous but averaged 16.5 passes per day with each pass being treated as an instantaneous snapshot of vessels (i.e. one location was selected for each vessel from each pass). This area was subdivided into a grid of 1 × 1 km^2. The mean density of shipping D_S in each square expressed in km travelled per km^2 per year (i.e. km^{-1} year^{-1}) was estimated from Eq. (1). This is the mean distance over all the satellite passes that the observed vessels

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Table 1
Dates of survey transects and effort achieved.

Date	Transect id. no. () indicates transect only partially completed		Total number of individual blue whales seen	Total survey effort on transect (km)
Surveys from *Raja and the Whales*				
18 Feb 2014	(10)	(11)	1	45
19 Feb 2014	9	10	17	91
21 Feb 2014	11	12	6	93
22 Feb 2014	(3)	(4)	7	65
28 Feb 2014	11	12	1	92
02 Mar 2014	13	14	5	91
04 Mar 2014	7	8	1	93
05 Mar 2014	9	10	2	92
06 Mar 2014	11	12	1	93
20 Mar 2014	1	2	52	93
21 Mar 2014	3	4	16	98
22 Mar 2014	5	6	18	93
23 Mar 2014	7	8	21	94
24 Mar 2014	9	10	2	94
31 Mar 2014	11	12	0	93
03 Apr 2014	13	14	0	93
16 Jul 2014	10	11	25	93
05 Oct 2014	10	11	1	93
06 Dec 2014	9	10	1	92
19 Dec 2014	9	10	0	93
13 Jan 2015	9	10	0	93
23 Mar 2015	1	2	0	93
24 Mar 2015	3	4	10	91
25 Mar 2015	5	6	6	93
26 Mar 2015	7	8	8	93
30 Mar 2015	9	10	15	93
31 Mar 2015	5	6	1	92
01 Apr 2015	7	8	11	92
02 Apr 2015	11	12	15	92
Total			**243**	**2616**
Surveys from *Mir*				
10 Mar 2015		1	0	46
17 Mar 2015		11	0	44
18 Mar 2015		10	1	46
19 Mar 2015	8	9	7	67
20 Mar 2015	11	12	0	86
23 Mar 2015	10	11	0	93
24 Mar 2015	13	14	0	85
02 Apr 2015	8	9	20	93
19 Apr 2015	13	14	10	92
Total			**38**	**652**

within a square would travel in one hour multiplied by the number of hours in a year (Leaper and Panigada, 2011).

$$D_S = 365 \times 24 \times 1.852 \times \frac{1}{P} \sum_{i=1}^{i=P} \sum_{j=1}^{n_i} v_{ij} \quad (1)$$

where P = number of satellite passes (in this case 5293)
n_i = number of vessels observed within a square on pass i
v_{ij} = the observed speed in knots of vessel j within that square on pass i (the multiplier of 1.852 converts speed in knots to km h^{-1}).

The simplest estimator of collision risk is the co-occurrence of whales and ships using the density of whales multiplied by shipping density in terms of distance travelled. This is the measure used in this study. Co-occurrence was also used in risk assessments by Redfern et al. (2013) and Bezamat et al. (2014) used a similar approach but included a term for vessel speed based on the risk-speed curve derived by Conn and Silber (2013). To estimate a crude index, N, of the likely number of interactions involving physical contact over a year (assuming no response by whales or vessels), we used the approach of Tregenza et al. (2000), giving

$$N = \frac{(B + 0.64L)}{1000} \times S \times D_S \times D_W \quad (2)$$

where

B = The beam of the ship in m (we used an average value of 32 m for a Panamax vessel)
L = Mean length of a whale in m (we used 20 m from Gilpatrick and Perryman, 2008)
S = Proportion of time spent at risk close to surface (we used 0.25 based on data in Croll et al., 2001 for feeding dives)
D_S = Shipping density (km^{-1} year^{-1})
D_W = Whale density (individuals km^{-2}).

3. Results

A total of 3268 km of full observational effort on pre-determined transects was conducted from both vessels combined. A total of 193 groups of blue whales was seen during this effort with a mean group size of 1.46, resulting in a total of 281 individuals. Locations of all sightings are shown in Fig. 1. During March and April 2015 two mother–calf pairs of blue whales were observed on the survey transects; these calves were judged to be very small although the actual age could not be estimated. The overall sighting rate from *Raja and the Whales* (0.06 individuals km^{-1}) for the 2015 season was similar to that from *Mir* (0.06 individuals km^{-1}). Hence although the two vessels had rather different characteristics

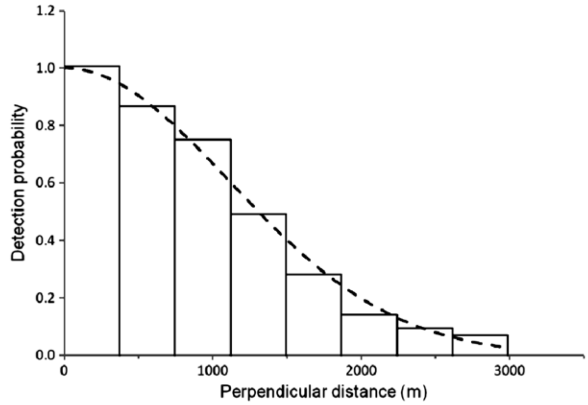

Fig. 2. Histogram of frequency distribution of observed perpendicular distances and detection function fitted using Distance (dotted line).

(mean survey speed for *Mir* was 5.1 knots compared to 6.3 knots for *Raja and the Whales*) it was thought appropriate to pool data from both vessels in a spatial model. However, only data from *Raja and the Whales* were used to generate a detection function which was pooled across all surveys.

Distance and angle data were available for 161 sightings. These were truncated at a perpendicular distance of 3000 m (removing three sightings) resulting in the detection function shown in Fig. 2. The estimated strip half width was 1301 m (95% CI 1136–1491 m). This strip width and the total effort of 2616 km of full transect gave a mean density estimate for all surveys of 0.036 individuals km^{-2}. For the survey area of 50 km by 150 km, this gives an approximate abundance estimate of 270 blue whales (CV = 0.09, 95% CI 226–322) assuming $g(0) = 1$. This CV does not make any allowance for measurement error in angles or distances to sightings. Sea conditions generally made use of reticle binoculars challenging and so distances were judged by naked eye and must be considered very approximate. The density estimates for comparable surveys in February to April 2014 (0.042 individuals km^{-2}) and March to April 2015 (0.034 individuals km^{-2}) show slightly lower densities in 2015.

For the spatial model, 129 of the 1 km segments of trackline had whales present, ranging from 1 to 14 animals within a segment. Sightability and sea state did not provide significant explanatory ability and were thus dropped from subsequent analysis. A combination of latitude, longitude and slope as covariates (see Fig. 3) gave a better fit (28.4% of deviance explained) than longitude, depth and slope (24.1% of deviance explained). Whale density increased with slope. However, it is likely that depth does have a strong influence over whale distribution, related to coastal upwelling. To explore this further, models using just depth were generated from three subsets of data, from surveys from *Raja and the Whales* from February 2014 to April 2014, surveys from *Raja and the Whales* from October 2014 to April 2015 and surveys from *Mir* from March to April 2015. All of these three models showed a consistent peak in blue whale density around depths of 800 m.

3.1. Shipping data

Shipping densities by 1 km square varied from 0 to 2200 km^{-1} year^{-1}. As expected, the highest values were in the main east-west shipping lanes close to the TSS. East of the TSS, shipping remained concentrated, whereas there was more dispersal further west (Fig. 4). When averaged across longitudes between 80° 30′E and 81°E, the peak mean density in the westbound lane was 1090 km^{-1} year^{-1} and in the eastbound lane 810 km^{-1} year^{-1}. These densities reflect the slightly greater total volume of westbound traffic overall. These can be compared to an estimate from 2007 of 280 km^{-1} year^{-1} for the main route across the eastern Mediterranean basin between the Strait of Sicily and the Suez Canal (Leaper and Panigada, 2011), and highlights that this is one of the densest areas of open ocean shipping anywhere in the world.

In addition to AIS data from large ships, data on the distribution of small fishing vessels were collected during the surveys. The total number of fishing vessels observed summed over all transects by latitude is shown in Fig. 5. Comparison to the distribution of vessels with AIS by latitude shows that fishing vessels tended to minimise the time spent in the shipping lanes but had to cross these to get further offshore. It was not possible to distinguish between boats actively fishing and boats travelling. In addition, much of the fishing activity occurs at night and so is not included in these observations. Nevertheless, based on these observations, if shipping lanes were to move 15 nm to the south and fishing activity remained unchanged, the number of fishing vessels encountered in the shipping lanes would be around 33% of the current situation.

Around 20% of shipping currently transits offshore of the TSS. Characteristics of a sample of 150 vessels transiting further offshore (randomly selected by MMSI number) in the AIS dataset were investigated. These included container ships, oil and chemical tankers, LNG and bulk carriers and ranged in size from 1000 to 200,000GT. Hence it appears that the choice of offshore route is not determined by size or type of vessel. There were also only very small changes in the proportion of vessels transiting offshore by month (minimum 18%, maximum 23%). Although there are distinct ‘lanes’ apparent for offshore traffic (zones A and B in Fig. 4) these lanes have two-way traffic with no separation between eastbound

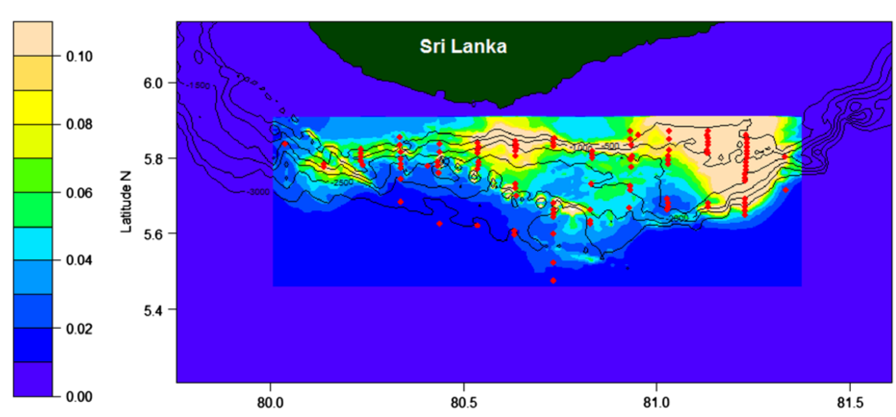

Fig. 3. Predicted whale density based on the full model using latitude, longitude and slope as covariates. Red circles indicate sightings on which model is based. Predictions are only given for the surveyed area. Scale is whale density as individuals km^{-2}. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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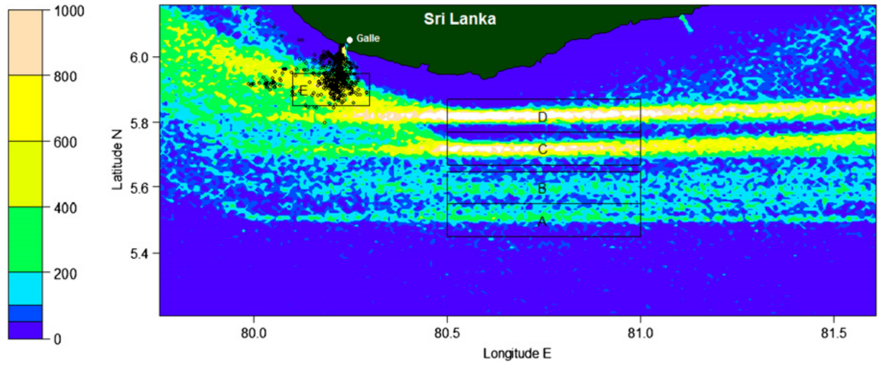

Fig. 4. Shipping density derived from satellite AIS data (see text for descriptions of zones A–E). Black circles show crew transfer vessels operating out of Galle. Scale is shipping density in km^{-1} year^{-1}.

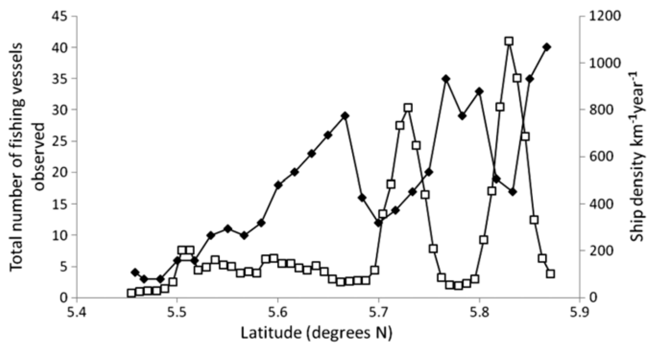

Fig. 5. Distribution of small fishing boats by latitude (black diamonds) and large ships (open squares). For fishing vessels the numbers are totals across the survey area for each latitude category, for large ships this is the average density across the survey area for each latitude category. The peaks in large ships reflect the current lanes associated with the Traffic Separation Scheme.

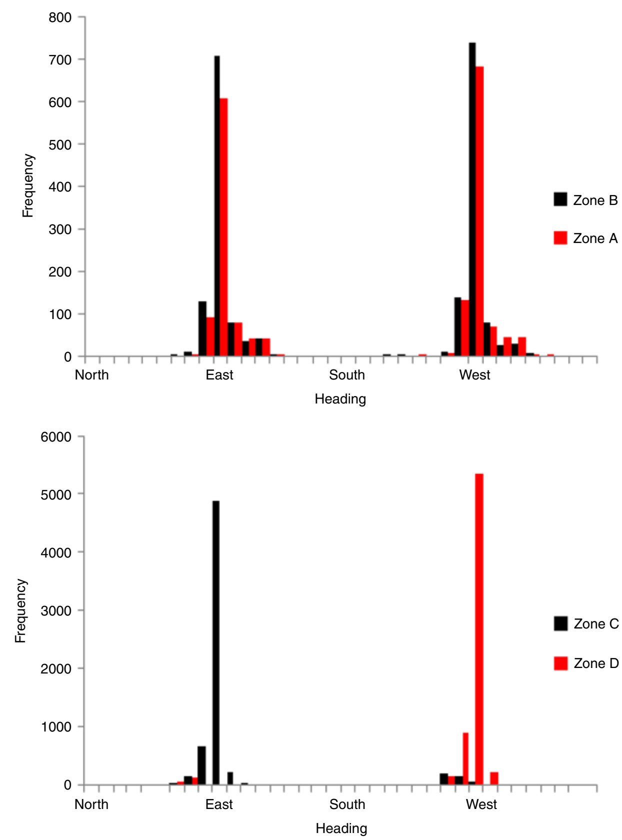

Fig. 6. (a) Distribution of vessel headings in Zones A and B and (b) Distribution of vessel headings in Zones C and D. Zones C and D have one way traffic associated with the Traffic Separation Scheme whereas traffic in zones A and B is two way.

and westbound as there is with the TSS. Within the TSS (zones C and D) almost all traffic follows the one way lane system (Fig. 6(b)), however, further offshore (zones A and B) there is an almost equal mix of east and westbound traffic (Fig. 6(a)) in both these zones.

Analysis of vessel tracks and headings shows that to the west of Sri Lanka, 31% of traffic (by number of vessels) appears bound for the Red Sea, 59% for the west coast of India or Arabian Gulf and 10% for Colombo or along west coast of Sri Lanka.

Vessel speeds in the main shipping lanes (zones A–D) were similar to typical global patterns (Fig. 7(a)) with a mean vessel speed of 13.9 knots. Zone E is an unusual area with ships coming close to the coast off Galle for transfer of security crews. In this zone, vessel speeds were much slower (Fig. 7(b)). The locations of crew transfer vessels are shown in Fig. 4.

3.2. Collision risk assessment

The estimate of the total number of interactions within the survey area at the time of the surveys, assuming no evasive response from whales or vessels, was 1016 per year. This is an order of magnitude greater than pessimistic estimates of the number of collisions occurring. Hence it is likely that the majority of situations that could result in a collision do not result in mortality. Nevertheless, the number of potential interactions gives an indication of the relative risk and can be used to evaluate the implications of changes in shipping patterns.

Fig. 8 shows an example of one possible change in shipping distribution. In this case, if the TSS was moved 15 nm to the south and all shipping east of 80° 09′E was concentrated in the red lanes shown, then the data from this study suggest the equivalent annual interaction rate across the survey area would be 51 (5% of the current situation).

4. Discussion

The results of surveys in 2014 and 2015 together with previous data indicate consistent high densities of blue whales occurring in the major shipping route south of Sri Lanka. The surveys described here were the first to systematically survey further offshore, and suggest much lower whale densities south of the current shipping lanes. These surveys were mainly conducted during the NE monsoon which typically lasts from December to April. However, the single survey in July 2014 during the SW monsoon also revealed similar distribution patterns. Blue whale presence in the study area has been reported for most months of the year but there are fewer whalewatching data from the SW monsoon period (June to October), as whalewatching activity is mainly concentrated during the inter-monsoon and NE monsoon periods. Blue whales

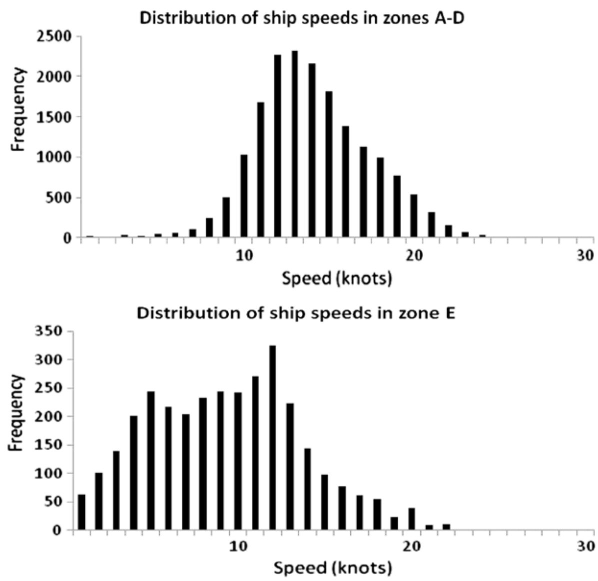

Fig. 7. (a) Distribution of vessel speeds in zones A–D (b) Distribution of vessel speeds in zone E.

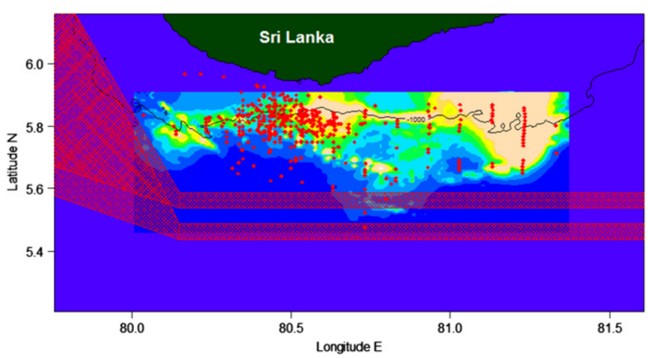

Fig. 8. Expected areas of high density shipping (red shading) if a TSS were established 15 nm to the south of the current scheme. Traffic is more dispersed to the west between shipping coming from the Red Sea and west coast of Sri Lanka. To the east almost all shipping is heading for Strait of Malacca. Coloured shading shows predicted whale density with the same scale as Fig. 3 for the rectangular survey area. Depth contour is 1000 m. Red circles indicate blue whale sightings from survey transects and whalewatching sightings from *Raja and the Whales*. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

have also been seen off the west coast of Sri Lanka, 30–190 nm offshore during the SW monsoon (Martenstyn, 2013). Data in the study area are particularly sparse from May to August when sea conditions make observations difficult. Continued survey work is planned to try to achieve some offshore effort throughout the year and to allow further investigation of inter-annual variability.

The southern coast of Sri Lanka has a narrow continental shelf and steep continental slope leading to an abyssal plain of 3–4000 m. Coastal upwelling driven by monsoon winds has been identified as the physical mechanism causing nutrient enrichment in the surface layer close to the southern coast. This upwelling is caused by converging coastal currents that generate an offshore flow creating a divergence at the coastline which maintains productivity during both monsoon periods (de Vos et al., 2013b). Highest surface chlorophyll (an indicator of primary productivity) concentrations have been observed during the SW monsoon but the circulation model of de Vos et al. (2013b) also predicts productivity during the NE monsoon and may explain the presence of feeding blue whales during this period. Vinayachandran et al. (2004) report high chlorophyll-a (*chl a*) occurrence close to the southern coast of Sri Lanka for all the summer (SW) monsoons during 1998–2002, suggesting that this is a regular seasonal feature. Between July and October, a narrow band of *chl a* exists along the southern coast of Sri Lanka but *chl a* decreases offshore (Vinayachandran et al., 2004). The consistency of these oceanographic processes suggests that the distribution patterns of blue whales are also likely to be consistent between years. Current patterns of shipping off the south coast run parallel to depth contours along the continental shelf slope in areas of much higher productivity than the abyssal plain further offshore.

The coincident very high densities of whales and shipping suggest a severe risk of ship strikes. Any deaths from collisions are likely to be substantially under-reported as most ships are unaware that they have struck a whale and the often strong surface currents in this area (Shankar et al., 2002) would take floating carcasses away from shore.

Although blue whales occur in much higher densities in this area than other large whale species, the distribution of other potentially vulnerable species should be taken into account. There were eleven sightings of Bryde's whales during this study and all these were north of 5° 36′N. Whalewatching data also suggest a more coastal distribution for Bryde's whales compared to blue whales. Two large groups of sperm whales were seen during the survey transects, in both cases close to the 1000 m depth contour. Sperm whales have also been seen in the survey area by whalewatching operators and during our study when not on transect between the 1000 and 2000 m depth contours. In other areas, sperm whale distribution is closely associated with the 1000 m depth contour and steep shelf slopes (Frantzis et al., 2013). Thus the possible alternative shipping routes further offshore shown in Fig. 8 would also be expected to reduce collision risks for sperm and Bryde's whales.

Calves and juveniles appear to be more vulnerable to ship strikes than adults, possibly due to a lack of awareness or a greater proportion of time spent at the surface (Laist et al., 2001). In addition to the two blue whale calves seen on survey transects, other blue whale calves were also seen when not on transect and calves are frequently reported by whalewatching operators. Small sperm whale calves were also observed, including one seen alone in the westbound shipping lane on 1 April 2015. The frequency of sightings of calves suggests that south of Sri Lanka is a nursery area for these species and that shipping may pose an even greater risk because of this.

The predictable pattern of blue whale distribution indicates the potential for measures to keep ships and whales apart. Such measures will need to take account of economic considerations for vessels visiting ports in Sri Lanka in addition to traffic on passage across the Indian Ocean. Coastal fishing activity also needs to be considered. Further, measures to reduce ship strike risk to blue whales may improve maritime safety for the whalewatching operators and fishing vessels. In addition, the current situation results in some shipping apparently being concentrated in unofficial shipping lanes to the south of the TSS. These concentrations of traffic have two-way flow, and safety could be enhanced by a routing scheme in these areas. For shipping in transit to or from the Red Sea, the additional distance of transiting through a TSS established 15 nm to the south of the current scheme would add around 5 nm to the total distance, 9 nm for traffic from west coast of India and Arabian Gulf, or 12 nm from Colombo. The data from the 2014 and 2015 surveys suggest that such a change in shipping patterns would reduce the risk of collisions with blue whales by around 95%. If the main shipping in transit were to shift further south as in Fig. 8, this would allow greater scope for an slower inshore traffic zone for vessels using Sri Lankan ports and particularly the new port at Hambantota. As further survey data become available, the estimates of likely risk reduction associated with changes to shipping can continue to be refined.

Acknowledgements

It is a pleasure to acknowledge the assistance of the crew of *Raja and the Whales*, Thomas Gordon, Tim Lewis, Mark Van Thillo and Kitty Currier who all helped with observations at sea. Shipping data were kindly provided by Dimitris Lekkas (Marine Traffic). Funding for this study came from the International Fund for Animal Welfare, Ward Foundation, Kopcho Foundation, and Swire Pacific Offshore.

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