Seasonal distribution, movements and taxonomic status of blue whales (*Balaenoptera musculus*) in the northern Indian Ocean

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ABSTRACT

There is a distinct population of blue whales, *Balaenoptera musculus*, in the northern Indian Ocean. The taxonomic status of these animals has long been uncertain, with debate over whether this population represents a distinct subspecies, and if so which name should apply. They have most frequently been assigned to *B. musculus brevicauda*, but are currently considered to be *B. m. indica*. The movements of these blue whales within the northern Indian Ocean are poorly understood. This paper reviews catches (n = 1,288), sightings (n = 448, with a minimum of 783 animals), strandings (n = 64) and acoustic detections (n = 6 locations); uses ocean colour data to estimate seasonality of primary productivity in different areas of the northern Indian Ocean; and develops a migration hypothesis. It is suggested that most of these whales feed in the Arabian Sea off the coasts of Somalia and the Arabian peninsula during the period of intense upwelling associated with the southwest monsoon (from about May to October). At the same time some blue whales also feed in the area of upwelling off the southwest coast of India and west coast of Sri Lanka. When the southwest monsoon dies down in about October–November these upwellings cease. The blue whales then disperse more widely to eke out the leaner months of the northeast monsoon (during about December to March) in other localised areas with seasonally high productivity. These include the east coast of Sri Lanka, the waters west of the Maldives, the vicinity of the Indus Canyon (at least historically), and some parts of the southern Indian Ocean. The data are consistent with the hypothesis that at least some of the blue whales that feed off the east coast of Sri Lanka in the northeast monsoon also feed in the Arabian Sea during the southwest monsoon. These whales appear to migrate eastwards past the north of Maldives and south of Sri Lanka in about December–January, returning westwards in about April–May.

KEYWORDS: BLUE WHALE; INDIAN OCEAN; STRANDINGS; SANCTUARIES; INCIDENTAL SIGHTINGS; MIGRATION

INTRODUCTION

> *'[Blue] whales are great travellers; a study of their distribution is largely a study of their migrations ...'* Mackintosh (1966)

There appears to be a distinct population of blue whales, *Balaenoptera musculus*, in the northern Indian Ocean (NIO) (Blyth, 1859; Branch *et al.*, 2007b; Yochem and Leatherwood, 1985). These whales hold a particular fascination for marine biologists for at least three reasons.

First, the taxonomy of these animals has long been unresolved. General understanding has been that they were probably pygmy blue whales, *Balaenoptera musculus brevicauda* (Ichihara, 1966) or of unknown taxonomic status (Alling *et al.*, 1991; Gordon *et al.*, 1986; Jefferson *et al.*, 2008; Rice, 1998; Yochem and Leatherwood, 1985). However, it is likely that they are a distinct subspecies, *B. m. indica* (Blyth, 1859). Certainly Blyth (1859) intended the name *indica* to apply to the common 'Great Rorqual' of the northern Indian Ocean. While there has been recent progress, uncertainty remains (Branch *et al.*, 2007b; LeDuc *et al.*, 2007; Perrin *et al.*, 2010; Rice, 1998), and we return to this issue in the Discussion.

Secondly, the NIO population of blue whales was subject to a short but intense period of illegal whaling by the former Soviet Union during 1963–1966. Catches were made during October–December (mostly November) as Soviet whaling fleets sailed south from Odessa for the Antarctic whaling season. At least 1,294 blue whales were taken from the Arabian Sea (Mikhalev, 1996; Mikhalev, 2000). While catch data were reported in Russian in 1982 (Zemsky and Sazhinov, 1994) they were not reported to the International Whaling Commission (IWC) at the time, nor were they made more widely available until much later (Berzin, 2008; Brownell, 1995; Clapham and Ivashchenko, 2009; Mikhalev, 1996; Mikhalev, 2000; Yablokov, 1994). The extent of population depletion and subsequent recovery are unknown. Although Zemsky and Sazhinov (1994) suggested that 90% of the initial stock may have been removed in the 1960s, their data do not agree with that of Mikhalev (1996; 2000), and recent sightings rates are relatively high in comparison with other regions (Branch *et al.*, 2007b). Reeves *et al.* (2004) highlighted the understanding of NIO blue whale population status and trends as priorities for research.

The third reason why NIO blue whales are of particular interest is that they appear to be concentrated in tropical waters year-round. This is in contrast to most other populations of blue whales which have been thought to typically (though not invariably) migrate between higher latitude summer feeding grounds, and lower latitude winter breeding areas (Branch *et al.*, 2007b; Burtenshaw *et al.*, 2004; Mackintosh, 1966; Mackintosh and Wheeler, 1929). The NIO does not extend north to the Arctic. But so entrenched was the idea that blue whales follow this typical migration strategy, that for decades it was assumed that NIO

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blue whales must migrate seasonally either to the Southern Ocean (de Silva, 1987; Deraniyagala, 1960) or to the north Pacific (Mörzer-Bruyns, 1971; Slijper *et al.*, 1964).

It now appears that most of these whales are resident within the NIO. This understanding is based on year-round sightings (Branch *et al.*, 2007b; Yochem and Leatherwood, 1985) and strandings (Anderson *et al.*, 1999; Branch *et al.*, 2007b; Ilangakoon and Sathasivam, 2012). There also appear to be gaps in the distribution of blue whales to both the south and east (Branch *et al.*, 2007b; Kasuya and Wada, 1991; Miyashita *et al.*, 1995; Zemsky and Sazhinov, 1994). For example, Zemsky and Sazhinov (1994) noted an absence of reports by Soviet whalers of blue whales from the central latitudes of the Indian Ocean and Bay of Bengal 'even though these regions were frequently visited by our boats' and concluded 'that pygmy blue whales of the Arabian Sea … form a local-subpopulation and their migration to the south is insignificant'. Although there is still some uncertainty (see Discussion), NIO blue whales also show distinctive biological characteristics, including: somewhat shorter length at sexual maturity (Branch and Mikhalev, 2008); breeding seasonality consistent with that of a northern hemisphere population (Mikhalev, 1996; 2000); low frequency of shark bite scars compared with southern Indian Ocean pygmy blue whales (Mikhalev, 2000); and unique 'Sri Lanka' call type (Alling and Payne, 1987; Alling *et al.*, 1991; McDonald *et al.*, 2006; Stafford *et al.*, 2011; Tolstoy and Bohnenstiehl, 2002).

Despite being largely restricted to the NIO, these blue whales do appear to undertake intra-regional migrations (Anderson, 2005; Anderson *et al.*, 1999). These migrations are the main subject of this paper.

METHODS

Study area

This study concentrates on the Maldives, southern India and Sri Lanka, but encompasses all of the northern Indian Ocean, west of 100°E and north of 10°S (Fig. 1). This southern boundary marks the approximate position of the thermal equator and a major oceanographic front (Longhurst, 1998; Wyrtki, 1973). These boundaries also enclose all of the discrete grouping of blue whale records in the Arabian Sea and adjacent waters (Branch *et al.*, 2007a; Mikhalev, 1996). Although this area extends to 10°S, for convenience we refer to it here as the northern Indian Ocean (NIO).

The meteorology of this region is dominated by the monsoons. During the southwest (SW or boreal summer) monsoon, winds over the Arabian Sea are predominantly southwesterly or westerly, blowing from the Horn of Africa towards India. During the northeast (NE or boreal winter) monsoon winds over the Arabian Sea are predominantly northeasterly. Winds in the NE monsoon are generally much lighter than in the SW monsoon. The approximate durations of the two monsoons are:

SW: May to October; and
NE: December to March.

The early months of both monsoons are generally windier and wetter than the later months. As a result, those later months are sometimes referred to as the post-monsoons,

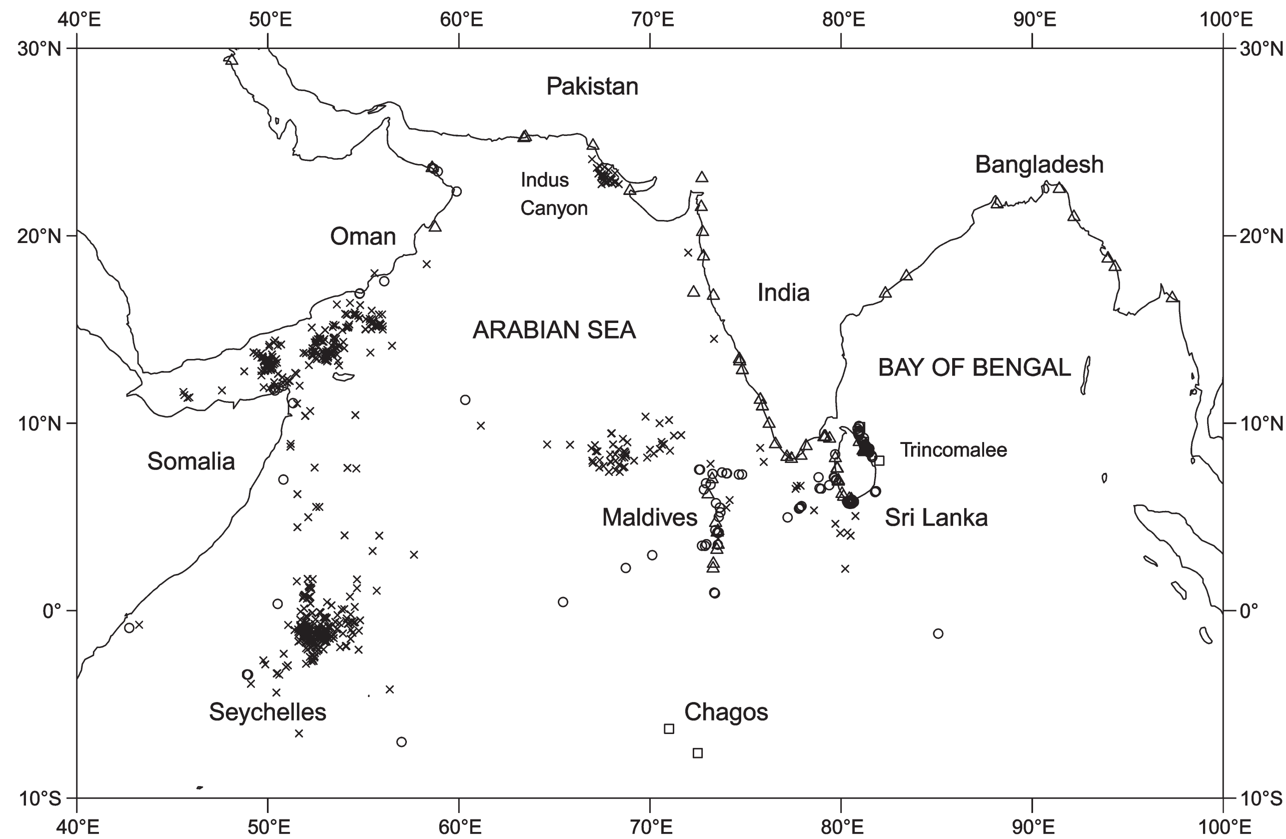

Fig. 1. Northern Indian Ocean location map, showing all known positions of blue whales catches (crosses, n = 1,288), sightings (circles, n = 396), strandings (triangles, n = 64) and acoustic detections (squares, n = 6 locations). Data from prior to 1973 are in grey; data after 1973 are in black. This figure is updated from Branch *et al* (2007b).

although wind direction remains more-or-less constant throughout each season. April and November are inter-monsoon months, when winds are generally variable. Monsoon timings vary slightly according to latitude. Due to the Coriolis force, the NE monsoon becomes the NW monsoon south of the equator while the SW monsoon derives from the austral SE monsoon.

The oceanography of this region is strongly affected by these seasonally reversing monsoon winds (Hydrographic Office, 2007; Molinari *et al.*, 1990; Schott, 1983; Schott and McCreary, 2001; Shankar *et al.*, 2002; Swallow, 1984; Wyrtki, 1973). During the SW monsoon, the strong winds blowing across the Arabian Sea towards India force the development of a clockwise circulation and promote upwelling off the coasts of Somalia and southwest Arabia. At the eastern boundary of the Arabian Sea (i.e along the west coast of India) this anticyclonic circulation flows southward as the West Indian Coastal Current and then eastward around the south of Sri Lanka where it joins with the Southwest (or Summer or Indian) Monsoon Current flowing into the Bay of Bengal. Within the Bay of Bengal itself, the East Indian Coastal Current flows northwards along the east (Coromandel) coast of India.

During the NE monsoon, most currents in the region reverse. The eastward flowing Southwest Monsoon Current is replaced by the westward flowing North Equatorial Current. The West Indian Coastal Current reverses, and flows northward along the southwest Indian (Malabar) coast. The East Indian Coastal Current reverses and flows southward for only a short period during the early part of the NE monsoon, being northward flowing for the remainder of the year.

In brief, throughout much of the NIO the general direction of flow in the SW monsoon is to the east, while during the NE monsoon it is to the west (although there are counter-currents south of the Equator). During the SW monsoon these currents induce significant upwellings off the coasts of Somalia, southwest Arabia and southwest India, as a result of which there are major plankton blooms in these regions at this season (Fig. 2). The upwellings, and their associated plankton blooms, die down during the NE monsoon.

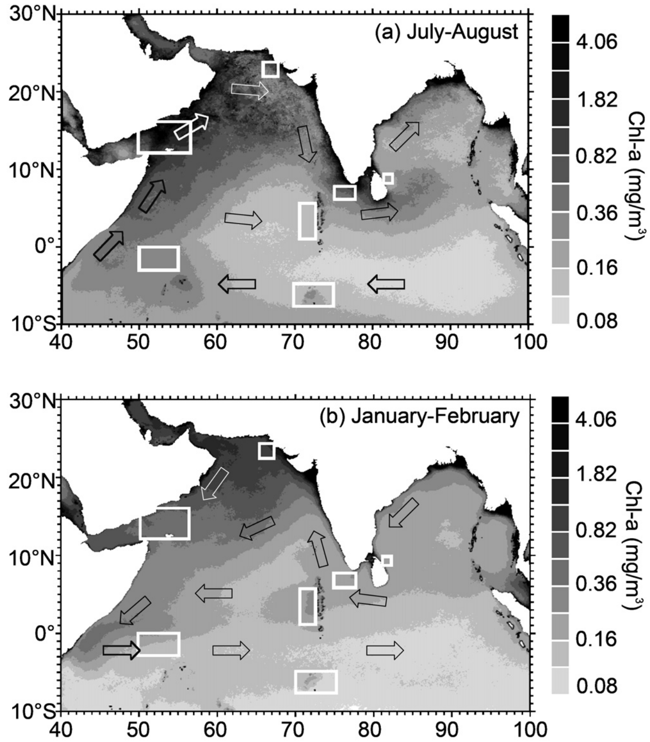

Fig. 2. Chlorophyll-a concentrations in the northern Indian Ocean (from SeaWiFS ocean colour data, see text for details). Boxes enclose areas for which seasonality of Chl-a have been estimated (see text for details). Arrows show schematic representation of major surface current directions. (a) July–August (SW monsoon). (b) January–February (NE monsoon).

Blue whale data

This study is largely based on published records of blue whale catches, sightings and strandings, most of which were previously compiled and critically scrutinised by Branch *et al.* (2007b) (see also de Silva, 1987; Leatherwood, 1986; Sathasivam, 2000). The wide-ranging study of Branch *et al.* (2007b) only briefly discussed the northern Indian Ocean, which we consider in more detail here. The Indian Ocean datasets they used (and we analyse further here) included: (a) Soviet catch data for the period 1963–66 (Mikhalev, 1996; 2000; Yablokov, 1994), which were made available by the Secretariat of the IWC; (b) published and previously unpublished records of sightings, the sources of which were summarised by Branch *et al*. (2007b: Appendix 2); (c) published and previously unpublished records of strandings, the details of which were tabulated by Branch *et al.* (2007b: Appendix 3); and (d) acoustic records, again documented by Branch *et al*. (2007b: Appendix 5) .

In this study the same datasets have been used, with some additions and minor alterations (Fig. 1). Leatherwood *et al.* (1984) reported nine sightings off NE Sri Lanka in February 1983, not May as recorded by Branch *et al.* (2007b: Table A2). It should also be noted that the position of the stranding reported by Lal Mohan (1992) from 'Paravana (12°10'N 76°30'E) near Calicut on 29-9-1988' must be incorrect since that location is inland; here a revised position of 11°15'N 75°47'E was used, which is near Calicut. Details of ten sightings from northeastern Sri Lanka by A.D. Ilangakoon are excluded from this study; they are instead included in the review of Ilangakoon and Sathasivam (2012). Some additional information has been incorporated in this review, including the published records of sightings by Carwardine (1994) and Afsal *et al.* (2008), and of one stranding each by Jayasankar *et al.* (2006) and Gray (2009).

New and previously unreported observations have also been collected. Two sightings from NE Sri Lanka in March 2004 have been included, which were supported by photographs (Chris Paporakis, pers. comm.). One of the authors (RCA, accompanied on two days by AA) visited southern Sri Lanka in April 2007, specifically to test the hypothesis that blue whales were migrating past at that time of year. Observations were made from Dondra Head (the southernmost point of Sri Lanka) on 18 and 19 April, and from a boat at sea off Dondra on 21 and 23 April 2007. Subsequently, records of blue whale sightings off southern Sri Lanka up to April 2009 were collected. These were based on observations by two of the authors (RCA and AA, $n = 117$ encounters), together with logbook records of a commercial boat tour company (Mirissa Watersports, $n = 96$ encounters), after the crew had received training in species identification

Table 1

Sightings of blue whales on voyages between India, Sri Lanka and Maldives. SW monsoon May to October. NE monsoon December to March.

				Blue whales (Sightings (individuals))		
Dates	Vessel	Start	Finish	ID definite	ID uncertain	Source
Jan. 3–5, 2004	*Hebridean Spirit*	Colombo	Malé	0	0	RCA (unpublished data)
Jan. 11–13, 2007	*Hebridean Spirit*	Colombo	Malé	0	0	RCA (unpublished data)
Jan. 13–14, 2002	*Hebridean Spirit*	Cochin	Malé	0	0	RCA (unpublished data)
Jan. 14–16, 2007	*Hebridean Spirit*	Malé	Cochin	0	0	RCA (unpublished data)
Jan. 15–17, 2002	*Hebridean Spirit*	Maldives	Galle	0	0	RCA (unpublished data)
Jan. 16–17, 2003	*Hebridean Spirit*	Cochin	Malé	0	0	RCA (unpublished data)
Jan. 18–20, 2003	*Hebridean Spirit*	Maldives	Galle	0	0	RCA (unpublished data)
Jan. 18–21, 2007	*Hebridean Spirit*	Kannur	Galle	0	0	RCA (unpublished data)
Jan. 20–25, 1983	*Tulip*	Colombo	Colombo	0	0	Alling *et al*. (1983)
Jan. 23–24, 2003	*Hebridean Spirit*	Colombo	Vilinjam	0	0	RCA (unpublished data)
Jan. 27–28, 2002	*Hebridean Spirit*	Cochin	Malé	0	0	RCA (unpublished data)
Jan. 31, 2003	*Hebridean Spirit*	Vilinjam	Colombo	0	0	RCA (unpublished data)
Feb. 4–5, 2003	*Hebridean Spirit*	Galle	Malé	0	0	RCA (unpublished data)
Feb. 9–12, 1982	*Tulip*	Arabian Sea	Colombo	0	0	Alling *et al*. (1982)
Feb. 12–17, 1984	*Tulip*	Malé	S of Sri Lanka	0	0	Alling *et al*. (1984)
Feb. 21–23, 2007	*Hebridean Spirit*	Colombo	Malé	0	0	RCA (unpublished data)
Feb. 19–Mar. 16, 1982	*Tulip*	Colombo	Colombo	0	0	Alling *et al*. (1982)
Mar. 29–30, 2003	*Odyssey*	Colombo	S of Sri Lanka	0	0	Ocean Alliance (2003)
Apr. 2–4 2003	*Odyssey*	S of Sri Lanka	Colombo	0	0	Ocean Alliance (2003)
Apr. 19–20, 1983	*World Discoverer*	Colombo	Malé	0	0	Leatherwood *et al*. (1984)
Apr. 21,1995	*Malcolm Baldrige*	8° Channel	Colombo	1 (1)	1(2)	Ballance *et al*. (1996)
Apr. 26–30, 2003	*Odyssey*	S of Sri Lanka	Colombo	0	0	Ocean Alliance, (2003)
Apr. 28, 1995	*Malcolm Baldrige*	Colombo	8º Channel	0	0	Ballance *et al*. (1996)
May 14–16, 2003	*Odyssey*	Colombo	Colombo	0	0	Ocean Alliance (2003)
May 23–27, 2003	*Odyssey*	Colombo	Colombo	0	0	Ocean Alliance (2003)
Jun. 16–17, 2003	*Odyssey*	Colombo	Colombo	1	0	Ocean Alliance (2003)
Jun. 16–21, 1995	*Malcolm Baldrige*	8° Channel	Malé	8 (13)	9 (12)	Ballance *et al*. (1996)
Nov. 6–27, 1983	*Tulip*	S of Sri Lanka	Malé	0	0	Whitehead *et al*. (1983)
Dec. 4–13, 1983	*Tulip*	Malé	Malé	0	0	Whitehead *et al*. (1983)

Table 2

Sightings of blue whales during crossings from Maldives to Seychelles (Malé to Mahé). January–February is NE monsoon (NW monsoon south of the Equator); April is inter-monsoon.

		Blue whales (Sightings (individuals))		
Dates	Vessel	ID definite	ID uncertain	Source
Jan. 21–25, 2004	*Hebridean Spirit*	2 (3)	0	RCA (unpublished data)
Feb. 21–24, 2010	*Discovery*	1 (2)	1 (1)	RCA (unpublished data)
Feb. 24–28, 2007	*Hebridean Spirit*	1 (2)	0	RCA (unpublished data)
Apr. 21–24, 1983	*World Discoverer*	1 (4)	0	Leatherwood *et al*. (1984)

from the senior author. In addition, RCA has completed a number of crossings between Maldives, Sri Lanka and India, and between Maldives and Seychelles on vessels of opportunity (cruise ships) during which cetacean watches were maintained. Details are summarised in Tables 1 and 2.

In total, records of 1,288 blue whale catches, 448 sightings, 64 strandings, and acoustic detections from 6 locations in the NIO have been compiled. For 296 sightings, numbers of individuals were recorded (n = 631, mean = 2.1 individuals per sighting). For the remaining 152 sightings, numbers of individuals were not available. Thus for all 448 sightings a minimum of 783 (631+152) individuals were recorded (note that sightings were compiled over several decades and there are known to have been some re-sightings, so this does not imply anything about population size). Only 396 sightings were recorded with location data of sufficient accuracy to be included in Figs 1 and 4.

Acoustic studies have demonstrated a unique call type for NIO blue whales. This was first recorded off Sri Lanka (Alling and Payne, 1987; Alling *et al.*, 1991) and subsequently around the Chagos Archipelago (Tolstoy and Bohnenstiehl, 2002). Until recently such studies were of limited value for understanding seasonality of NIO blue whales. However, while this paper was in review, an analysis of two years' monitoring of blue whale calls around Chagos became available (Stafford *et al.*, 2011) and is of great relevance for this investigation.

A number of limitations in our data can be noted. In particular, it was not possible to standardise effort. Our analyses of sightings are therefore based on raw incidental data, not sightings rates. This can clearly lead to problems of interpretation. We do, however, have an understanding of seasonal variations in sea conditions (which affect sightability), and some knowledge of relative amounts of effort between subregions and seasons. For example, in both Sri Lanka and the Maldives, more sightings effort has been conducted in the NE monsoon (which is relatively calm, particularly in its later months) than in the generally much rougher SW monsoon. Further analysis as more detailed data become available is planned to address this shortfall. It should also be noted that blue whale strandings depend, among other things, on wind and current directions, which in this region vary dramatically with the seasons.

Chlorophyll-a concentrations

Blue whales feed almost exclusively on euphausiids. Although some information is available (e.g. Brinton and Gopalakrishnan, 1973), the seasonal distribution of euphausiids in the tropical Indian Ocean is not known in sufficient detail to be of direct use in this study. We have therefore used chlorophyll-a concentrations (hereafter Chl-a) as a proxy for blue whale food. There are limitations to this approach (e.g. that Chl-a may not adequately reflect primary productivity; that deep chlorophyll maxima may not be adequately accounted for in the data used; that there will be lags between Chl-a and euphausiid abundance peaks; and that there may be spatial and temporal variability in any relationship between Chl-a and euphausiid abundance). Nevertheless, in the absence of more appropriate data, this approach does allow a first investigation of some factors influencing the seasonal distribution of blue whales in the NIO, and highlights areas for further study.

Chl-a concentrations were quantified using monthly composites of the 9-km Level 3 SeaWiFS data, from the NASA Goddard Space Flight Center (GSFC) Distributed Active Archive Center (DAAC) (McClain *et al.*, 1998). The reflectance values of the original data files were converted into chlorophyll concentrations using the empirical algorithm of O'Reilly *et al.* (1998). The dataset used is for the period September 1997 to December 2008, which represents a sequence of 136 monthly images. For the purposes of this study we have estimated the seasonal distribution of Chl-a for seven areas (Fig. 3), which are delineated in Fig. 2 and have the following boundaries:

Gulf of Aden:	12°–16°N, 50°–57°E
North of Seychelles:	0°–3°S, 50°–55°E
Indus Canyon:	22°–24°N, 66°–68°E
West of Maldives:	1°–6°N, 70.5°–72.5°E
West of Sri Lanka:	3°–12°N, 74°–80°E
NE Sri Lanka:	8°–9°N, 81°–82°E
Chagos:	5°–8°S, 70°–75°E

The choice of box boundaries was to some extent subjective, and there is undoubtedly scope for further refinement in future studies. Areas where blue whales were suspected to be feeding seasonally were investigated, not necessarily where they might be transiting. Thus, in the case of the Maldives our box was placed west of the atoll chain (where blue whales may be feeding during the NE monsoon), not over it (where the larger number of blue whale records are suspected to be of transiting animals). In the case of the western Arabian Sea, this is a vast area, and we have used the Gulf of Aden as a representative subarea, where many blue whales were caught by Soviet whalers (Fig. 1).

RESULTS

Seasonal distributions of Chl-a for seven areas within the NIO are given in Fig. 3. Both the Gulf of Aden and the

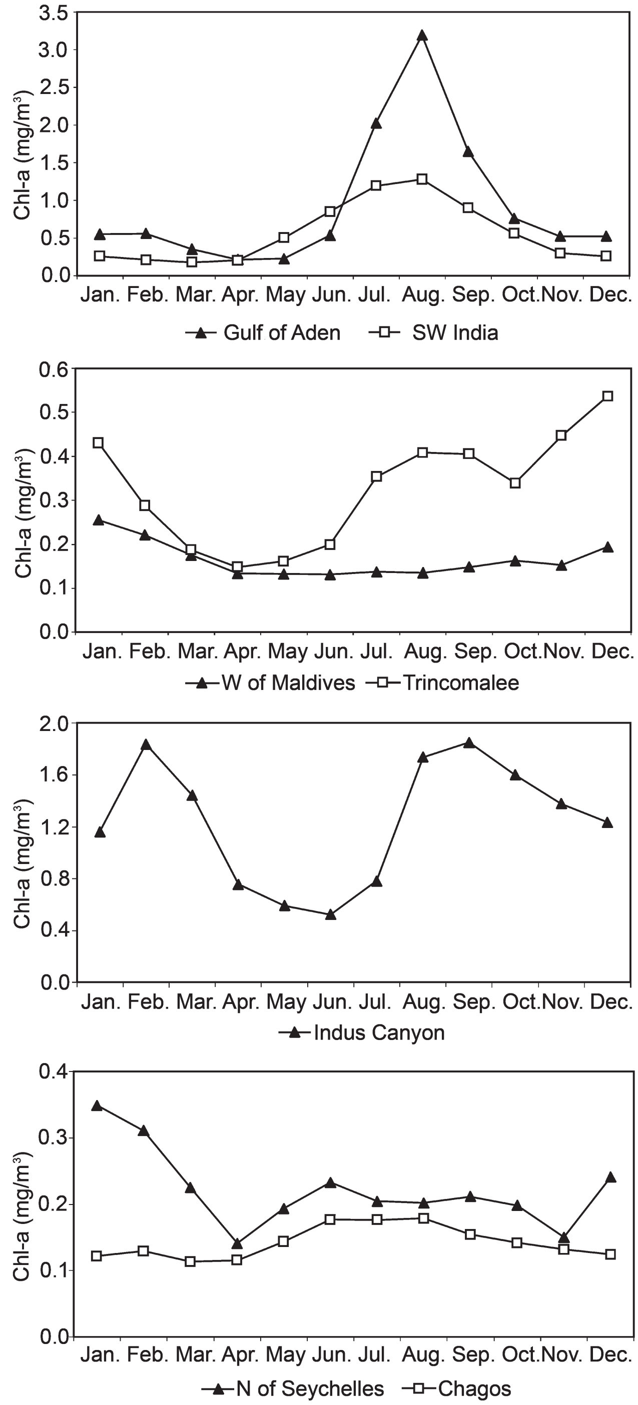

Fig. 3. Seasonal distribution of Chl-a in seven areas of the northern Indian Ocean, corresponding to boxes in Fig. 2 (from SeaWiFS data, see text for details; note different scales). SW monsoon May to October, NE monsoon December to March.

waters off SW India showed marked seasonality in Chl-a, with clear peaks from about June or July to September, i.e. during the southwest monsoon. In contrast, the area west of Maldives, which has much lower Chl-a overall, shows a peak in Chl-a during December to March, i.e. during the northeast monsoon season. Trincomalee on the east coast of Sri Lanka also shows a peak in Chl-a during the northeast monsoon season, notably during November to January. A second, lesser peak in August–September is likely associated with the increased run-off from the Mahaweli River during the latter part of the southwest monsoon. The Indus Canyon area shows distinctly bimodal seasonality, with Chl-a peaking in

February–March (northeast monsoon) and August–October (latter part of southwest monsoon). The former is possibly associated with local upwelling, the latter with increased run-off from the Indus River associated with the SW monsoon. The area north of Seychelles also shows bimodal seasonality in Chl-a, with peaks in both monsoon seasons. In the waters around the Chagos, Chl-a is low year-round, with a slight seasonal peak in June–August. These results are consistent with existing knowledge (e.g. Banse, 1968; Currie *et al.*, 1973; Darbyshire, 1967; Longhurst, 1998; Smith and Bottero, 1977; Smith, 1984; Vinayachandran *et al.*, 2003).

All available blue whale records from the NIO are mapped in Fig. 1. The same records are presented by month in Fig. 4. All Soviet catches were made during Oct–Dec, so by themselves they tell us relatively little about seasonal distribution. Most captures were actually made in November, which is the transition between the SW and NE monsoons.

Seasonality of blue whale sightings within different areas of the NIO is summarised in Fig. 5 (note that sightings are not available from all areas, so fewer areas are included in Fig. 5 than in Fig. 3). In addition, summaries of blue whale sightings made during crossings between Maldives, India and Sri Lanka are presented in Table 1. Blue whales were recorded in both June voyages, and during one of five April voyages, but not during other months. The relatively large number of crossings between mid-January and March suggest that blue whales are not common in this area at this time. Summaries of blue whale sightings made on four crossings between Maldives and Seychelles are presented in Table 2. Blue whales were recorded west of Maldives on each of the four crossings, suggesting that they are relatively common in this area, at least during January–April. Numbers of sightings of blue whales on a standard transect off Trincomalee, Sri Lanka, completed by the RY *Tulip* during 1983–84 are summarised in Table 3 (Alling *et al.*, 1991; Whitehead, 1983).

Strandings within the NIO are clearly concentrated in the South Asian region (Fig. 1). Further west, around the Horn of Africa and on the southern Arabian coast, there is only one stranding reported. Numbers of strandings in different parts of South Asia (Pakistan and NW India; SW India and west Sri Lanka; Maldives; and Bay of Bengal) are summarised by month in Table 4, and by time period (before and after the period of Soviet whaling) in Table 5. The area including the coasts of Pakistan and NW India had the highest number of recorded strandings up to 1967, but has had no reported strandings since that time. In contrast, the Maldives (where there was almost no cetacean research conducted prior to the 1980s) had no recorded blue whale strandings prior to 1985. Seasonality of strandings by area is illustrated in Fig. 6.

DISCUSSION

Blue whales are the largest animals that have ever lived, and have particularly high prey demands, which they meet by seeking out areas of particularly high productivity (Croll *et*

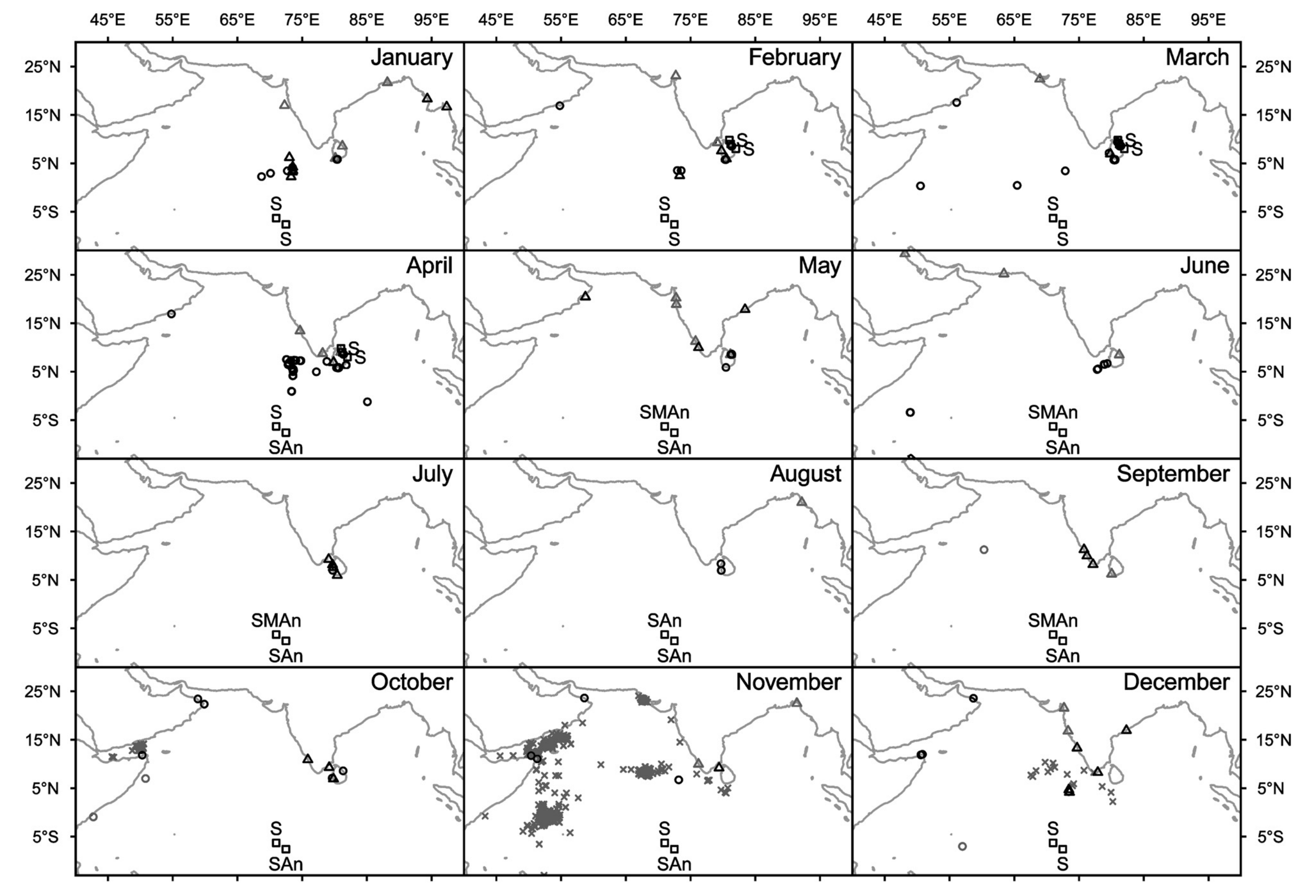

Fig. 4. Monthly distributions of blue whales in the northern Indian Ocean, showing all known positions of catches (crosses), sightings (circles), strandings (triangles) and acoustic detections (squares: S = Sri Lankan, M = Madagascan, An = Antarctic call types). Data from prior to 1973 are in grey; data after 1973 are in black. This figure is modified from Branch *et al.* (2007b). SW monsoon May to October, NE monsoon December to March.

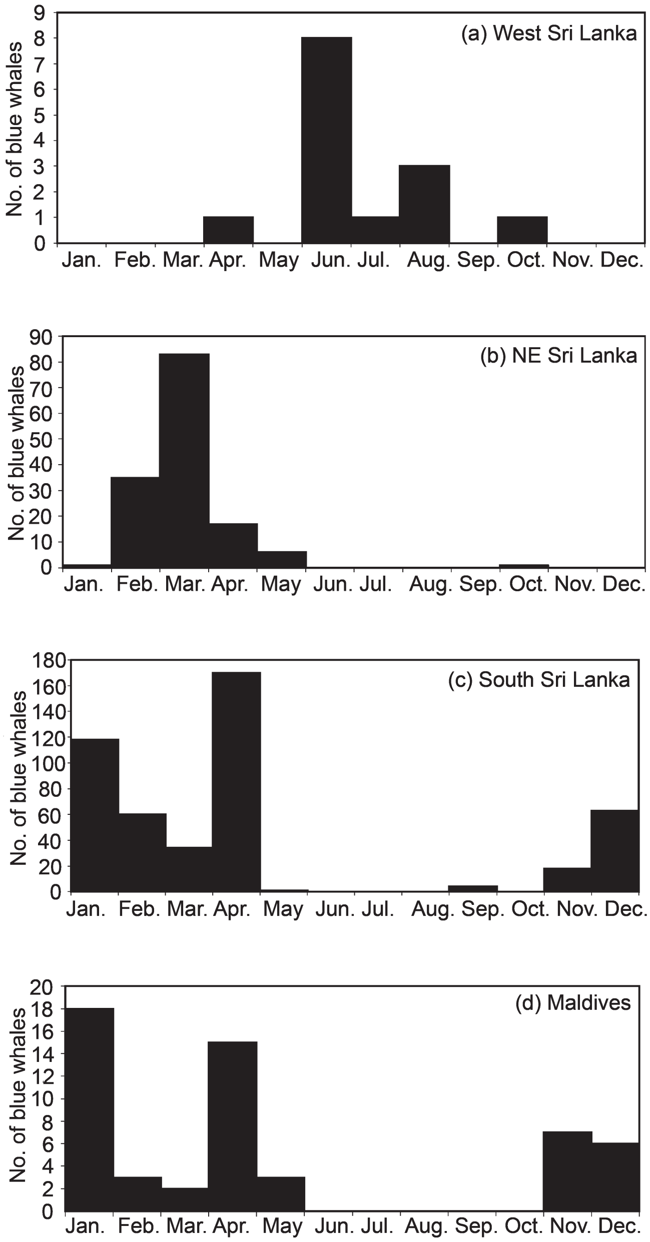

Fig. 5. Sightings of blue whales by month from four areas in the central Indian Ocean: (a) west Sri Lanka, $n = 14$ blue whales; (b) NE Sri Lanka, $n = 143$; (c) south Sri Lanka, $n = 468$; and (d) Maldives, $n = 54$. SW monsoon May to October, NE monsoon December to March.

al., 2000). We assume that NIO blue whales are no different from other blue whales in this regard, and that they too search out areas of especially high krill (euphausiid) abundance. Since regions of high productivity within the NIO shift with the seasonally changing monsoon currents, we expect that the whales do so too. Indeed some intra-regional movements have already been proposed (Anderson, 2005; Anderson *et al.,*1999).

Strandings of blue whales in south Asia (Maldives, India and Sri Lanka) are known to occur year-round, but peak during the NE monsoon (Anderson *et al.*, 1999). This well-defined seasonal pattern of strandings implied that there were migrations within the NIO, with many blue whales moving away from south Asia during the SW monsoon. It was suggested that the most likely destination for these whales was the western Arabian Sea (Anderson *et al.*, 1999). In that area, during the SW monsoon, intense upwelling off the coasts of Somalia and Arabia, combined with open-ocean Ekman pumping, promote a major plankton bloom (Figs 2a and 3); in fact, this is one of the most productive seasonal upwellings in the world ocean (Longhurst, 1998).

Table 3

Sightings of blue whales along standard transect off Trincomalee (NE Sri Lanka) from RV *Tulip*. SW monsoon May to October, NE monsoon December to March.

Date	No. blue whales	Source
12 Mar. 1983	7	Alling *et al.* (1991)
22 Mar. 1983	23	Alling *et al.* (1991)
24 Apr. 1983	0	Alling *et al.* (1991)
16 Oct. 1983	1	Whitehead *et al.* (1983)
2 Nov. 1983	0	Whitehead *et al.* (1983)
22 Feb. 1984	3	Alling *et al.* (1991)
11 Mar. 1984	7	Alling *et al.* (1991)

Sightings of blue whales in the Maldives were subsequently shown to occur during November to April (Anderson, 2005). Noting that blue whales occurred off the NE coast of Sri Lanka near Trincomalee during December to April (Alling *et al.*, 1991; Leatherwood *et al.*, 1984; Leatherwood and Reeves, 1989), Anderson (2005) suggested that if at least some of these 'Sri Lankan' whales also fed in the Arabian Sea during the SW monsoon, then they must migrate via the Maldives in April. As he noted, Ballance and Pitman (1998) had previously documented the presence of numerous blue whales in the Eight Degree Channel at the northern end of the Maldives archipelago in April.

In brief, the hypothesis tested and developed here is that many blue whales in the NIO feed in the highly productive zones associated with the major SW monsoon upwellings, namely in the western Arabian Sea and off the SW coasts of India and Sri Lanka. With the change of monsoon in October–November, these upwellings stop, and within a month or so zooplankton concentrations also dissipate. The blue whales then disperse more widely in the NIO to seek out other, more localised zooplankton concentrations.

Thus it is predicted that: during the SW monsoon blue whales occur in the upwelling areas of the NW Arabian Sea and off the SW coast of India and west coast of Sri Lanka; during the NE monsoon blue whales occur in other (smaller or lesser) productive areas within the NIO; and that during intermonsoon periods, peaks in abundance of blue whales occur in intermediate areas as the whales pass between SW and NE monsoon feeding grounds. In the absence of detailed information on the seasonality of euphausiids throughout the NIO, we use satellite-derived Chl-a data to provide a rough proxy for blue whale forage. We note that it may take one or two months for zooplankton biomass to build up at the beginning of each upwelling season, while later in the season zooplankton grazing may keep Chl-a low even while production is high. Blue whale abundance may therefore lag peak Chl-a (Croll *et al.*, 2000).

Blue whales in the western Arabian Sea

A major prediction of this migration hypothesis is that blue whales should be found in areas of high productivity in the western Arabian Sea (including the Gulf of Aden) during the SW monsoon season. This is a wide area, and we have used

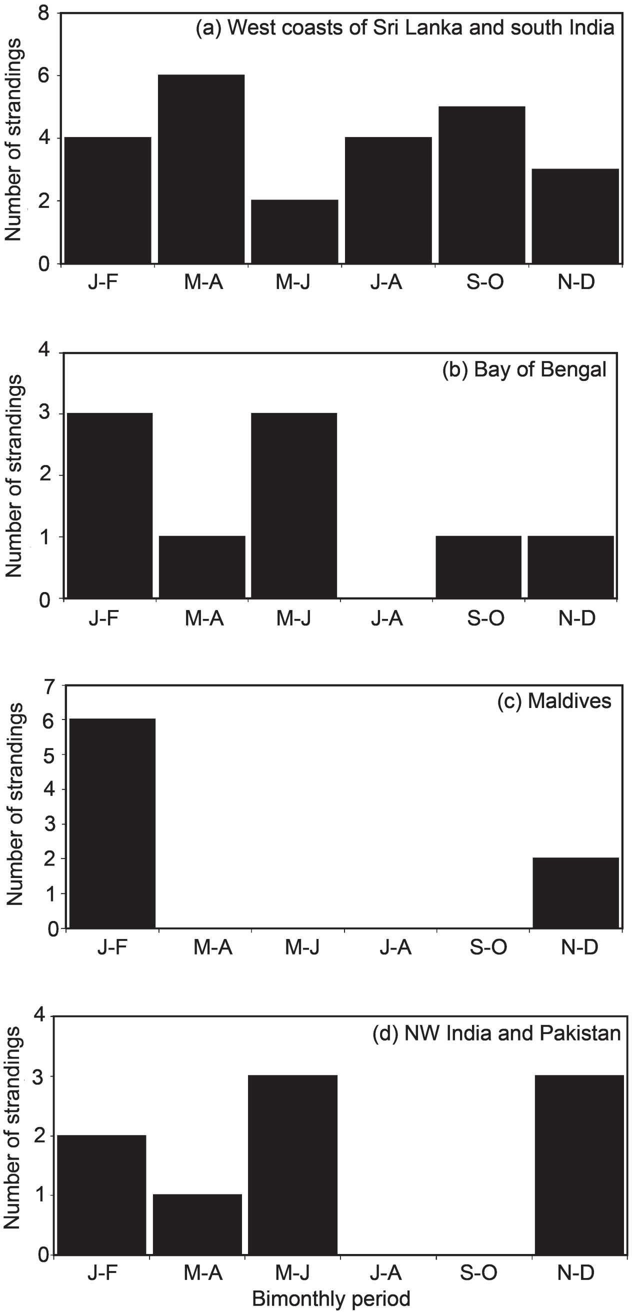

Fig. 6. Strandings of blue whales by bimonthly period from four areas in the central Indian Ocean: (a) west Sri Lanka and SW India; (b) Bay of Bengal; (c) Maldives; (d) NW India and Pakistan. SW monsoon May to October, NE monsoon December to March.

Table 4

Strandings of blue whales by month for major regions in south Asia. (Southwest = west coasts of Sri Lanka and south India, south of 12°N. Northwest = coasts of Pakistan and west India, north of 12°N). SW monsoon May to October, NE monsoon December to March.

	Bay of Bengal	Southwest	Northwest	Maldives	Total
Jan.	3	1	1	5	10
Feb.	0	3	1	1	5
Mar.	0	1	1	0	2
Apr.	1	5	0	0	6
May	2	2	2	0	6
Jun.	1	0	2	0	3
Jul.	0	4	0	0	4
Aug.	0	0	0	0	0
Sep.	1	3	0	0	4
Oct.	0	3	0	0	3
Nov.	0	2	0	0	2
Dec.	1	1	2	2	6
Total	9	25	9	8	51

Table 5

Strandings of blue whales before and after 1967, for major regions in south Asia. (Southwest=west coasts of Sri Lanka and south India, south of 12°N. Northwest=coasts of Pakistan and west India, north of 12°N).

	Bay of Bengal	Southwest	Northwest	Maldives	Total
1967 and before	9	10	11	0	30
1968 and after	5	15	0	8	28
Total	14	25	11	8	58

the Gulf of Aden as a representative subarea for Chl-a analysis, while recognising that finer scale analyses are desirable. Within the Gulf of Aden there is a very marked peak in Chl-a during July–September (Fig. 3). Elsewhere in the Arabian Sea, ocean colour data (which we have analysed but do not present here) show that in the Somali Basin, Chl-a increases rapidly in May as upwelling starts, and peaks during June–September. For the western Arabian Sea as a whole it is therefore likely that zooplankton (and thus potentially blue whale) abundance is high from about June–July to October or November.

Blue whales are certainly present in the western Arabian Sea from at least September to November. Nineteenth century sperm-whalers recorded blue whales on the 'Arabian grounds' during September to November, with one vessel reporting 'lots' off the Somali coast at 7°N 50°49'E in October 1888 (Wray and Martin, 1983). Slijper (1962, p.337) noted 'records made by some Dutch officers who reported, *inter alia*, that on 23rd September, 1953, 30–50 Blue Whales in groups of 3–4 were seen over an area of about ten square miles in the Indian Ocean (at 11°15'N and 60°13'E)'. The wording of this report is similar to that of Mörzer Bruyns (1971), suggesting that he may have been one of the Dutch officers concerned. Mörzer Bruyns (1971: chart 14) also recorded blue whales off the Horn of Africa and Socotra during September–November, as well as noting that he 'encountered them [during] several southern winters well east of Socotra Island and also in the Gulf of Aden'. In the 1960s, Soviet whalers took many blue whales in the Gulf of Aden and western Arabian Sea during October–November (Figs 1 and 4; Mikhalev, 1996; 2000; Yukhov, 1969).

There is, however, little evidence for the predicted presence of blue whales in the western Arabian Sea, or indeed in most other parts of the NIO, during the period June–August. Some authors have taken this as evidence that blue whales must move out of the NIO at this time of year (e.g. de Silva, 1987; Deraniyagala, 1960; Slijper *et al.*, 1964). However, a more satisfactory explanation is that sea conditions are simply too rough during June–August for any useful cetacean surveys. Several researchers have noted the difficulties of observing cetaceans in the northwest Indian Ocean at this time of year, when the SW monsoon is at its most fierce (e.g. Ballance and Pitman, 1998; Eyre, 1995; Reeves *et al.*, 1991; Small and Small, 1991). Small and Small (1991) carried out no survey work at all off the Indian

Ocean coast of Somalia during June–September. Eyre (1995) provided data which illustrate the impact of poor observing conditions during this season. She rounded the Horn of Africa in late June 1993. During the 9-day period 26 June to 4 July inclusive, there were 8 days with an average sea state of 4 or more, and one day with an average sea state 2. During those 8 rough days, she recorded just two sightings. In contrast, on the one calmer day she recorded no less than 15 cetacean sightings. There is clearly a need for more work during the rough SW monsoon season; remote technologies such as satellite tracking and acoustic monitoring may provide the means to do so.

It is predicted that there should be relatively few blue whales in the open Arabian Sea during the NE monsoon season, when productivity is relatively low (Figs 2b and 3). There is indeed a lack of offshore sightings during January to April (Fig. 4). Sea conditions are usually relatively calm throughout much of this season, when there are reports of sperm whales for example (Ballance and Pitman, 1998; Mörzer-Bruyns, 1971; Slijper *et al.*, 1964). So one might expect at least some reported sightings of blue whales if they were present in numbers. Nevertheless, in the absence of sighting effort data, this cannot be taken as unequivocal evidence for a lack of blue whales. Furthermore, it is possible that some blue whales may loiter in coastal locations with elevated productivity during the NE monsoon season.

In contrast to some other areas within the NIO (see below), there is no evidence for blue whale seasonality in the western Arabian Sea from strandings data. Indeed, there is only a single reported stranding from the entire Arabian and NE African coasts, in Oman in May (Figs 1 and 4). The reason(s) for this dearth of strandings are unknown, but there are at least two possibilities. One is that there may be less likelihood of strandings being detected and reported on these sparsely populated coasts than on the much more densely populated coasts of the Indian subcontinent. A second possibility is that blue whale strandings along the western seaboard of the Arabian Sea may be genuinely rare. In support of this second possibility, we note that fairly comprehensive reports of strandings from Oman had until very recently failed to report a single blue whale stranding (Collins *et al.*, 2002; Gray, 2009). The hypothesis presented here predicts that blue whales are most abundant off these coasts during the SW monsoon when the prevailing winds are offshore; the likelihood of any dead whale being cast ashore must therefore be greatly reduced. In addition it seems likely that many of the blue whales in this region occur some distance offshore (Fig. 1), again reducing their chances of stranding. One reason for this may be that the inshore upwelling food chains along these coasts are dominated by copepods and myctophids rather than euphausiids (Smith *et al.*, 1998; Smith, 1984).

SW India and west of Sri Lanka

During the SW monsoon, the long-shore flow of the West Indian Coastal Current induces upwelling along the SW coast of India, promoting a major phytoplankton bloom there (Banse, 1968; Darbyshire, 1967; Longhurst, 1998). This productive water is carried southward around the west and south coasts of Sri Lanka, where it is enhanced by further upwelling (Vinayachandran *et al.*, 2003), before being transported eastwards with the SW Monsoon Current into the Bay of Bengal (Figs 2a and 3).

It is predicted that blue whales should occur in this area of high productivity from about June to October or November and be absent or rare when productivity is low during the NE monsoon season (Fig. 3). Again, rough weather during the SW season has restricted opportunities for cetacean surveys. Nevertheless, the limited data from the west coast of Sri Lanka (Fig. 5a) do support this prediction: there are no reported sightings of blue whales during the calm NE monsoon, despite several surveys at that season (Table 1; Leatherwood and Reeves, 1989), but there have been sightings during the rough SW monsoon. Ilangakoon (2002) 'frequently encountered' blue whales off the west coast of Sri Lanka during May to October 1994, and there have been other reports of sightings in June (De Vos *et al.*, 2011; Asha de Vos, pers. comm.) and August (Bröker and Ilangakoon, 2008). Further offshore, in the area between Sri Lanka, India and Maldives, blue whales were recorded in June by Ballance and Pitman (1998), and in November by Soviet whalers (Fig. 4).

It is also predicted that blue whales travelling between the western Arabian Sea and the east coast of Sri Lanka (see below) should transit this area in about December and April–May. While there have been no offshore sightings in December (Table 1), there were several catches by Soviet whalers in November and December (Fig. 4). It is, however, not clear if these catches were of blue whales which had spent the SW monsoon feeding locally or whales which were in transit from the western Arabian Sea. And with only a single offshore sighting from April (Table 1 and Fig. 4), this is one area where additional survey work and/or satellite tracking will be required to test our predictions.

Despite this shortcoming, there is further support for this migration hypothesis from strandings records. Strandings on the west coasts of southern India and Sri Lanka occur more-or-less year-round (Fig. 6a, Table 4). But the peaks in strandings during April and July (Table 4) are consistent with our predictions of relatively large numbers of blue whales transiting this area in April, and feeding offshore in July. The relatively small numbers of strandings (just two) in December and early January, at a time when relatively large numbers of blue whales are predicted to be transiting the area is also to be expected, since winds and currents are offshore at this season. This is reflected in the peak of strandings downstream, in the Maldives, during December and early January (see below).

NE Sri Lanka

It has been known for many decades that blue whales occur off the east coast of Sri Lanka. Deraniyagala (1948) noted that blue whales 'commonly occur off Ceylon' [Sri Lanka] and that 'the abundance of whales and their proximity to land off Trincomalee is particularly noteworthy'. Even earlier, Blyth (1859) considered the 'great rorqual' to be relatively common throughout the northern Indian Ocean, including Sri Lanka, and specifically noted the stranding of a whale which he apparently considered to be *B. indica* 'in Ceylon … near Trincomali'. However, the presence of blue whales there was largely forgotten by marine biologists, and their rediscovery in February 1983 came as something of a surprise (Whitehead, 1983; 1989).

The seasonality of these blue whales has not been well established, since most fieldwork has been conducted during the NE monsoon season (e.g. Alling *et al.*, 1991; Carwardine, 1994; Leatherwood *et al.*, 1984). However, Gunaratna *et al.* (1985) stated that blue whales were seen off Trincomalee from November to mid-May, while Alling *et al.* (1991) noted that few were recorded after April. The sightings data that we have compiled support the contention that most blue whales occur in this region during the NE monsoon season, with recorded sightings peaking during February–April (Fig. 5b). We note that this area can be quite rough at the beginning of the NE monsoon, with strong onshore winds during December–January, so the dearth of sightings in those months may not reflect genuine absence. Indeed, there is a peak in strandings in January (Table 4), which suggests that at least some blue whales are present off NE Sri Lanka at this time, despite so few sightings.

The absence of blue whales from this area during the SW monsoon is not well established from sightings, since relatively little time has been spent at sea in this area at this season. But during one 16-day survey off NE Sri Lanka during October–November 1983 (by the RY *Tulip*), only one blue whale was recorded (Whitehead, 1983). Other data collected from the RY *Tulip* included sightings from a standard 20 n.miles (36km) transect running due E–W off Trincomalee; despite limited coverage during the SW monsoon, these data could suggest that blue whales are scarce in this area between late April and November (Table 3). Records of strandings in the Bay of Bengal are consistent with this pattern of seasonality, with 75% of strandings occurring during the period November to May. In addition, this pattern of blue whale seasonality is consistent with the seasonality of Chl-a (Fig. 3b), which peaks in November–January, suggesting peak zooplankton abundance during approximately December–March. The observed pattern of Chl-a seasonality may be heavily influenced by seasonally variable run-off from the Mahaweli Ganga (Sri Lanka's largest river), which enters the sea at Trincomalee (Alling *et al.*, 1991). In addition, physical processes may concentrate blue whale prey in the vicinity of the submarine Trincomalee Canyon, where blue whales congregate (Alling *et al.*, 1991).

While most blue whale strandings in the Bay of Bengal occur during the NE monsoon season, a few do occur during the SW monsoon. Whether these represent a few stragglers, or a regular year-round occurrence, remains unclear. Also, the distribution of strandings around the Bay of Bengal occurs over a much wider area than the distribution of known sightings, which are largely confined to the east coast of Sri Lanka. The disparity between the distributions of sightings and strandings no doubt in part reflects the distribution of observer effort. But it might also be partly explained by the fact that the East India Coastal Current flows northwards for most of the year, and therefore may disperse carcasses originating from near Sri Lanka more widely around the coasts of the Bay of Bengal. Soviet scientists certainly believed that the lack of blue whales in much of the Bay of Bengal was genuine, and that this was the result of relatively low plankton productivity (Zemsky and Sazhinov, 1994). Recent studies in Bangladeshi waters have not yet reported any blue whales (Smith *et al.*, 2008). Nevertheless, further surveys within the Bay of Bengal would be valuable.

Southern Sri Lanka

If blue whales are indeed largely absent from the NE coast of Sri Lanka after about April, the question arises, where do they go? The migration hypothesis presented here suggests that blue whales from Trincomalee are migrating to the Arabian Sea. They are unlikely to do so around the north of Sri Lanka, since the Palk Straight is so shallow, being just 10m deep in the dredged shipping channel (Hydrographic Office, 2007). Therefore it is predicted that blue whales must pass around the south of Sri Lanka in about April–May.

To test this prediction, the southernmost tip of Sri Lanka, Dondra Head, was visited in April 2007. Several blue whales were seen on every one of four days of observation. All of these sightings were in the vicinity of what appears, from the rather inadequate charts of this area, to be a canyon off Dondra Head. As a result of this finding, commercial whale watching has developed rapidly in the south of Sri Lanka, centred on the fishing port of Mirissa (just a few km west of Dondra). Most blue whales sighted by that operation appear to be associated with the continental slope.

Gunaratna *et al.* (1985) previously reported a sighting of two blue whales off Dondra Head on 7 May 1984. They further noted that since blue whales were seen off Trincomalee from November to mid-May, but apparently not at other times, these whales might migrate south to the south coast of Sri Lanka in the northern spring. Alling *et al.* (1991) did not speculate on migratory destinations of the blue whales they observed off Trincomalee, but they did present a diagram summarising blue whale swimming directions during February to April 1984 (Alling *et al.*, 1991; Fig. 5) which suggests a net southward trend.

Sightings data collected off the southern tip of Sri Lanka since 2007 (Fig. 5c) are bimodally distributed, with peaks in December–January and April. A very similar pattern is seen in the Maldives (Fig. 5d). Such patterns are consistent with an eastward movement of blue whales at the beginning of the NE monsoon (after zooplankton production associated with SW monsoon upwellings in the Arabian Sea has died down) and a westward return at the end of the NE monsoon. Off southern Sri Lanka blue whales have been seen travelling eastward during November–January (AA, pers. obs.). This is a rather extended period; perhaps if blue whales from both the western Arabian Sea and SE Arabian Sea (i.e. the SW coast of India and west coast of Sri Lanka) migrate to the Bay of Bengal after the end of the SW monsoon, they may pass eastwards at slightly different times, although this is no more than speculation at present. It was noted, however, that in both southern Sri Lanka and Maldives, although some blue whales seen at these times are travelling in the expected directions, others are not. Rather, they appear to be loitering, or even moving in the 'wrong' direction, and some are clearly feeding (diving repeatedly in the same area, and defecating). We also note frequent sightings of mother and calf pairs in March and April (RCA and AA, pers. obs). This is consistent with an April peak in calving estimated for Arabian Sea blue whales by Mikhalev (2000). Sightings of blue whales breaching in March and April (RCA and AA, pers. obs.) might also suggest a peak in reproductive activity at this time. However, the reproductive cycle of NIO blue whales is probably more complex than this suggests, with another calving peak possibly in October, notably among blue whales from Seychelles waters (Mikhalev, 2000).

Leatherwood and Reeves (1989) reported on several short surveys carried out, mostly by Sri Lankan scientists, off the south coast of Sri Lanka during the 1980s. Blue whales were not seen during surveys conducted in September, October, November and March. But blue whales were seen in December, both during a vessel survey, and from shore. More recently, Afsal *et al.* (2008) noted the presence of blue whales off the south coast of Sri Lanka in February and August.

In summary, we believe that many of the blue whales seen off the south coast of Sri Lanka are migrating between the Arabian Sea (including the west coast of Sri Lanka) and the Bay of Bengal (particularly the east coast of Sri Lanka). However, when food is present they may linger.

The Maldives

The seasonality of blue whale sightings in the Maldives is distinctly bimodal (Fig. 5d). This is similar to the pattern recorded from southern Sri Lanka (Fig. 5c), and can be explained in a similar way. During November to early January, blue whales pass eastward via the Maldives en route to the east coast of Sri Lanka. In April they return en route to the major upwelling areas of the western Arabian Sea. The relative scarcity of blue whales in February and March is genuine, not an artefact of survey effort, since a relatively large amount of time has been spent at sea in those months (RCA, unpublished data; Anderson, 2005). However, the lack of sightings in May likely reflects decreased survey effort in that month as the SW monsoon starts to take effect.

Blue whale strandings in the Maldives are highly seasonal, with all strandings recorded so far occurring during the short period December to February (Fig. 6d). This is consistent with the known pattern of sightings. During December–January, any blue whale that dies while passing through the Maldives or on towards Sri Lanka will be carried back by the westward-flowing North Equatorial Current, and may strand in the Maldives. In contrast, any blue whale that dies while travelling westward in April–May from Sri Lanka will be carried away from the Maldives and back towards Sri Lanka by the eastward-flowing Southwest Monsoon Current. This also suggests that most blue whales pass by the north of the Maldives (cf. Ballance and Pitman, 1998): if more passed through the Maldives Archipelago itself in April, then some strandings at that time might be expected.

All of the blue whale strandings observed in the Maldives in this study were of carcasses that appeared to have been dead and drifting for some days. During December–February, the prevailing North Equatorial Current flows to the west at about 1–2 knots (*ca*. 2–3 km/h) (Hydrographic Office, 2007). A blue whale that died off the coast of Sri Lanka would therefore drift westward, and might strand in the Maldives after about 10–12 days. There is evidence to support this scenario from a tragic source: after the tsunami of 26 December 2004, human corpses originating from Sri Lanka washed up in the Maldives from 12 days later.

While some blue whales must die of natural causes while passing between the Maldives and Sri Lanka, blue whales transiting southern Sri Lanka do pass through one of the busiest shipping lanes in the world. Ship strikes are an increasing cause of whale mortality worldwide (e.g. Berman-Kowalewski *et al.*, 2010; Laist *et al.*, 2001; Van Waerebeek *et al.*, 2007), and it is likely that some blue whales are killed by ship strikes in this region.

Although most blue whales appear to pass by the Maldives biannually, some blue whales may loiter. In particular, during the NE monsoon there is a regular increase in plankton productivity on the downstream (western) side of the atolls (Figs 2a and 3; Anderson *et al.*, 2011). It is therefore predicted that some blue whales should be found west of the Maldives during the NE monsoon season. This does in fact appear to be the case, with blue whales being sighted west of Maldives on each of four crossings to Seychelles (Table 2). They may therefore be relatively common in this area, at least during January–April. We also have unconfirmed reports from Maldivian fishermen and foreign big-game fishermen of blue whales west of Maldives at this season.

NE Arabian Sea

In the NE Arabian Sea, Soviet catches included at least 31 blue whales taken in November 1966, from the coastal waters of India and Pakistan (the Indo-Pakistani aggregation of Mikhalev, 2000). This area is known to have a particularly high abundance of zooplankton (Paulinose and Aravindakshan, 1977; Qasim, 1982) including euphausiids (Brinton and Gopalakrishnan, 1973). In this general area high catches of yellowfin tuna (*Thunnus albacores*), whale shark (*Rhincodon typus*) and humpback whale (*Megaptera novaeangliae*) have also been recorded (Mikhalev, 1997; Pravin, 2000; Vivekanandan and Zala, 1994).

More specifically, the Soviet blue whale catches were centred on the Indus Canyon (around 23°N 67°E). Elsewhere in the world, blue whales are known to associate with submarine canyons, for example the Monterey Canyon off California (Croll *et al.*, 2000) and the Perth Canyon off Western Australia (Rennie *et al.*, 2009). In those cases, physical oceanographic processes associated with the canyons promote the formation and maintenance of dense krill swarms on which the blue whales feed. Within this region, blue whales have been reported to be associated with the Trincomalee Canyon off NE Sri Lanka (Alling *et al.*, 1991), the Basses Canyon off SE Sri Lanka (De Vos *et al.*, 2012), and the Dondra Canyon off southern Sri Lanka (see above). On the other hand, there are as yet no reports from the Swatch-of-no-ground Canyon off Bangladesh (Smith *et al.*, 2008). Nevertheless, it seems possible that searches in the vicinity of other canyons within South Asian waters during appropriate seasons might reveal other concentrations of blue whales.

Regarding the seasonality of blue whales near the Indus Canyon, all Soviet catches were taken in November, at the beginning of the NE monsoon. Strandings from this general area all occurred during December–June, i.e. during or immediately after the NE monsoon (Fig. 6d, Table 4). There are no strandings reported from July–November. Since winds are onshore for most of that time, it seems likely that blue whales are absent from the area for much of the SW monsoon season. The pattern of Chl-a seasonality in the vicinity of the Indus Canyon is complex (Fig. 3), but Chl-a is elevated between August and March. Zooplankton abundance may be highest from about October. This supports the suggestion that blue whales are commonest in this area during the NE monsoon.

All of the strandings from Pakistan and NW India in our compilation occurred before the period of Soviet whaling in the 1960s (Table 5). Prior to that period, blue whale strandings appear to have been relatively frequent. Kinnear (1915), for example, noted 'quite a number' of strandings of what were presumably this species in the vicinity of Bombay (Mumbai). Since 1967 there have been no confirmed, published reports of blue whale strandings within this area (Branch *et al.*, 2007b: Appendix 3), although there was one unconfirmed report by Ali *et al.* (2002). This lack of recent strandings, and of recent sightings (Gore *et al.*, 2012), suggests that Soviet whaling may have seriously depleted, perhaps even extirpated, this small component of the NIO blue whale population. A survey of the Indus Canyon area would be desirable.

Seychelles

In November 1964, Soviet whalers took exactly 500 blue whales in the vicinity of the Seychelles (Mikhalev, 1996; 2000), within the area bounded by 0°–3°S and 50°–54°E. These catches may have substantially impacted blue whales in this area; when one Soviet whaling fleet returned from the Antarctic in April 1965, no blue whales were seen here (Mikhalev, 2000), although that might also reflect seasonality of occurrence. Subsequently there have been very few post-whaling reports of blue whale sightings from the vicinity of Seychelles (Eyre, 1995; Kasuya and Wada, 1991; Robineau, 1991); those few reported with dates occurred in March and June. There are no strandings from this area, and the Chl-a data also provide few clues, since there are peaks in both the SW and NE monsoons (Fig. 3). The seasonality of blue whales in this area therefore remains unclear.

Chagos

The Chagos Archipelago (officially known as the British Indian Ocean Territory) lies south of the Maldives, in 6–7°S. It is home to a US military base, on the island of Diego Garcia. No blue whale catches, sightings or strandings have been recorded. However, the International Monitoring System has maintained two underwater listening stations nearby for many years, in support of the Comprehensive Test-Ban Treaty, and these have detected blue whales in the vicinity. Using these acoustic monitoring data, Stafford *et al.* (2011) demonstrated that blue whales with a Sri Lanka call type (i.e. NIO blue whales) were present year-round in Chagos waters, but with a major peak in calls detected during April–May and a lesser peak in December–January (Fig. 7). The extent to which blue whales might be present but not calling at non-peak times is unknown. Nevertheless, this bimodal distribution corresponds rather closely with the bimodal distributions of blue whale sightings recorded here for both southern Sri Lanka and Maldives. Thus at least some NIO blue whales may be migrating through these waters biannually, travelling from the Arabian Sea during December–January. Where they are travelling to is unknown, but Stafford *et al*. (2011) raised the possibility that they are migrating to the southern Indian Ocean, since Sri Lanka calls have also been recently recorded near Crozet (in 46°S) in relatively low numbers but with a peak in December–February (Samaran *et al.*, 2010).

Chl-a is relatively low year-round in Chagos, with just a minor peak in June–August (Fig. 3), implying a peak in zooplankton abundance from about July or August onwards. Sri Lanka call detections are at a minimum during July–September (Fig. 7; Stafford *et al.*, 2011). If NIO blue whales are absent when food is possibly at its most plentiful, it seems unlikely that Chagos is a significant feeding area for these animals.

SE Arabian Sea

In the southern Arabian Sea, to the NW of Maldives, Soviet whalers caught over 300 blue whales (Fig. 1). All were taken

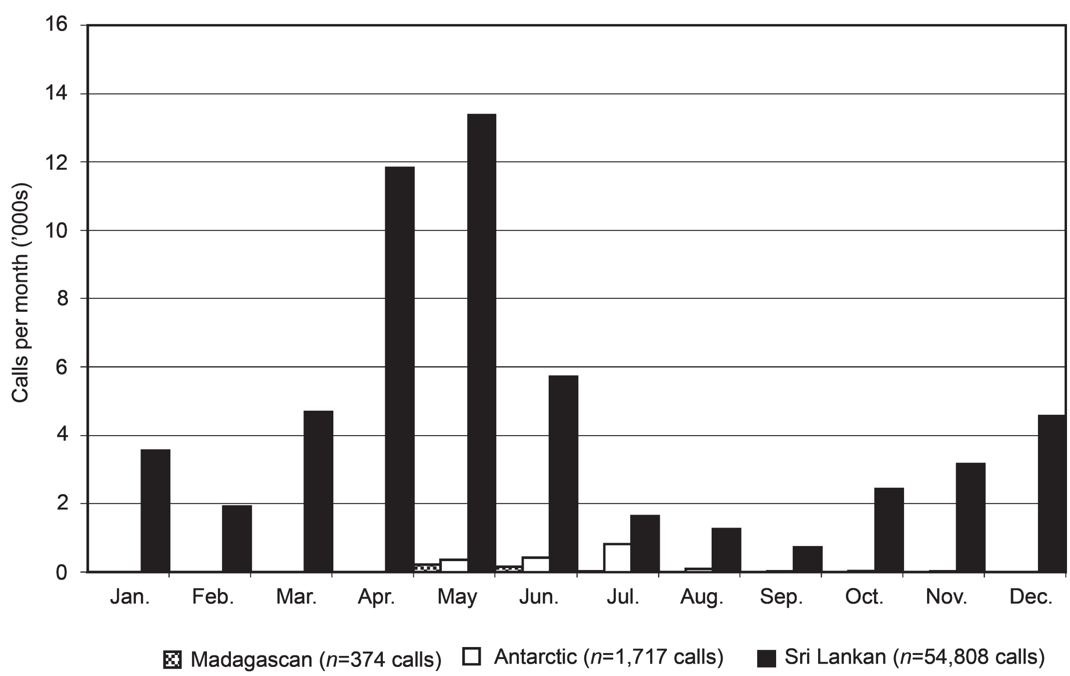

Fig. 7. Acoustic detections of three blue whale call types (Sri Lankan, Antarctic and Madagascan) near Diego Garcia (Chagos Archipelago) by month. Redrawn from Stafford *et al.* (2011) combining data from two listening stations supplied by K. Stafford. Diego Garcia is south of the Equator, so seasons differ from areas further north: SE monsoon May to October, NW monsoon December to March.

in November and December, mostly in 1964. Some were undoubtedly feeding, since they were caught with full stomachs (Mikhalev, 1996; 2000). However, relatively more blue whales from this area were taken with empty or near-empty stomachs (47%) compared with animals taken from the two other main areas exploited by the Soviets, namely the Gulf of Aden (32%) and north of Seychelles (23%) (Mikhalev, 1996; 2000). Ocean colour data (analysed by us but not presented here) show that mean Chl-a is relatively low (of the same order as that off the west of Maldives and Chagos). We think it possible that at least some of the blue whales caught to the northwest of Maldives may have been transiting the area; the timing of captures (in November and December) is certainly compatible with an eastward movement from the western Arabian Sea to the Maldives and Sri Lanka as predicted here. But this is another area where further studies would be welcome.

On *Balaenoptera indica* Blyth, 1859

Perrin *et al.* (2010) have recently inspected Blyth's holotype in Kolkata/Calcutta, India, confirmed that it is a blue whale, reviewed available information, and suggested that the name *B. musculus indica* (Blyth, 1859) should apply to the blue whales in the northern Indian Ocean. While that conclusion appears reasonable, it is not clear if this name should apply to these blue whales alone, since it has precedence over *B. m. brevicauda* (Ichihara, 1966). Furthermore, the degree of differentiation between northern and south Indian Ocean pygmy blue whale populations (or Sri Lanka, Madagascar and Australia call types) is still not well understood. There remains debate about the level of evidence needed to elevate blue whale populations to the status of subspecies (Branch *et al.*, 2007a; 2008; 2009). A standard definition of a subspecies includes two components: geographic isolation and distinguishing biological features (Branch *et al.*, 2007a). Regarding geographic isolation, this did seem fairly well established for NIO blue whales, but the recent recording of Sri Lanka type blue whale calls in the southern Indian Ocean suggest that things are not so clear cut (Samaran *et al.*, 2010). Regarding distinguishing biological features, although Perrin *et al.* (2010) cited the difference in length of female maturity between NIO blue whales and southern Indian Ocean pygmy blue whales as evidence of distinctiveness, this difference is small (just 0.5–0.6m) and there is overlap between putative populations (Branch and Mikhalev, 2008). The usefulness of this trait as a subspecific characteristic is therefore debatable. Another potentially distinctive trait of NIO blue whales is breeding seasonality consistent with that of a northern hemisphere population (Mikhalev, 1996; Mikhalev, 2000), although that understanding is based on sampling in predominantly just one month (November), and there was some suggestion of two breeding seasons (Mikhalev, 1996; 2000). In addition, the one genetic study conducted so far failed to separate northern from southern Indian Ocean 'pygmy' blue whales, although it included just two samples from the NIO (LeDuc *et al.*, 2007). In contrast, Chilean blue whales differ in length by 2m from both Antarctic and southern Indian Ocean blue whales (Branch *et al.*, 2007a), and are also genetically distinct (LeDuc *et al.*, 2007); but these whales are not currently considered to be a separate subspecies. Further studies, including additional acoustic and genetic analyses, are needed to clarify population separation within the Indian Ocean. In addition, satellite tracking could not only test the migration hypothesis presented here, but also help delineate stock boundaries. It is already known that at least some NIO blue whales wander beyond the boundaries considered in this study. It is likely that their stock status, as well as their seasonal distributions and migrations, will prove to be more complex than the relatively simple scenario presented here.

Another source of uncertainty, raised by Rice (1998), was that Blyth's 'type specimen … was 84ft (25.6m) long, and another individual 90ft (27.4m) long was reported, whereas the largest *brevicauda* ever taken was only 79ft (24.1m) long'. The longest Arabian Sea blue whale caught and measured by Soviet whalers was recorded as 24.0m (see also Gordon *et al.*, 1986; Mikhalev, 1996). But Blyth (1859) himself noted that the 90ft length he reported was 'as alleged' and the other stranding was 'stated to have been 84ft. in length', suggesting that any measurements may not have been especially accurate. Furthermore, it was common practice in the 19th and early 20th centuries to measure whales to the tip (rather than the central notch) of the flukes; no NIO stranding since 1927 has exceeded 24.1m reported length (Branch *et al.*, 2007b). Chari (1951) presented both measurements from one specimen of '*Balaenoptera indica*', the difference between them being about 8%. Applying this figure to the 84ft type specimen gives an estimated length of 23.6m. Blyth (1859) noted that the mandibles of this specimen were 'within less than 2 [inches] of 21 ft' i.e. 6.35m. From four strandings in the Maldives (lengths 16.8–22.9m, mandible lengths 4.82–5.50m, RCA unpublished data) mean mandible length was 26.6% (range 24.1–28.8%) of total length. Applying this figure to the 6.35m mandibles of the type specimen gives an estimated total length of 23.9m. The close agreement between these two total length estimates gives some confidence that the 'true' (i.e. central notch) length of this specimen may have been < 24m. We recognise that the conversion factors and estimates used here may not be highly accurate. But they nevertheless demonstrate that the reservation of Rice (1998) is, by itself, insufficient to dismiss Blyth's taxon.

The possibility that individuals of other subspecies of blue whale, for example Antarctic blue whale *B. m. intermedia*, occur in the NIO at least occasionally should be mentioned. Some strandings of very large blue whales have been recorded from the Indian region, including for example a 94ft (28.7m) individual stranded near Cochin in November 1927 (Moses, 1947). It is likely that most such cases are the result of incorrect measuring or reporting. However, the possibility of Antarctic blue whales straying north of the Equator, particularly in earlier days before commercial whaling reduced that subspecies to less than 1% of its original abundance (Branch, 2007; Branch *et al.*, 2004), cannot be entirely dismissed. Certainly, there is acoustic evidence of Antarctic-type blue whale calls in the vicinity of the Chagos Archipelago, where both Sri Lanka and Madagascar type calls have also been recorded (Stafford *et al.*, 2004; 2011). And LeDuc *et al.* (2007) presented genetic evidence (albeit from other regions) of blue whale vagrancy.

CONCLUSIONS

The available data suggest that there is a distinct population of blue whale, which should probably be known as *B.*

musculus indica, in the NIO. This population shows parallels with the Arabian Sea population of humpback whale, *Megaptera novaeangliae*, which also appears to be resident year-round in these tropical waters, to have a Northern Hemisphere breeding cycle, to be reliant on the SW monsoon upwellings and to have been heavily impacted by Soviet whaling in the 1960s (Mikhalev, 1997; 2000; Minton *et al.*, 2008; Reeves *et al.*, 1991).

It is proposed here that most of the NIO blue whales feed in the Arabian Sea off the coasts of Somalia and southern Arabia during the period of intense upwelling associated with the SW monsoon. At the same time some of these blue whales feed in the area of enhanced productivity off the southwest coast of India and west coast of Sri Lanka. When the SW monsoon dies down in October these upwellings cease. The blue whales subsequently disperse more widely, searching out other areas of enhanced productivity to last them through the leaner months of the NE monsoon.

One such NE monsoon feeding area is off the east coast of Sri Lanka. It is suggested that at least some of the blue whales feeding there originate in the western Arabian Sea. They must pass by the north of Maldives and south of Sri Lanka in November–January, while heading eastwards, returning westwards in April–May. Other blue whale feeding areas during the NE monsoon include the waters west of the Maldives and in the vicinity of the Indus Canyon. However, there have been no recent records from the NE Arabian Sea, which suggests the possibility that the Indus Canyon component of the NIO blue whale population may have been extirpated by Soviet whaling in the 1960s. Soviet whalers also caught large numbers of blue whales north of Seychelles; again, there have been few observations from that area since.

As more data become available, the use of abundance indices, such as sightings per day (rather than just sightings with no measure of effort, as used here) should provide more refined insights into blue whale seasonality in the region. However, even our crude data reveal patterns of seasonality that are consistent with our predictions, and with recent acoustic analyses, and do not simply reflect sightings conditions. Thus, blue whales have been sighted off the west coast of Sri Lanka (Fig. 5a) during the rough SW monsoon season (as predicted) despite the poor sea conditions and limited effort at that season. However, they have not been recorded there during the calmer NE monsoon (again as predicted) despite good sea conditions and greater effort during that season. Furthermore, the bimodal distribution of sightings off both southern Sri Lanka and the Maldives (Figs 5c and 5d) is consistent with our prediction of a biannual passage of blue whales through those waters. This cannot be explained by variations in sighting effort alone: there is for example a peak in sightings in Maldives in January, even though there has been much less sighting effort in that month than in either February or March (RCA, pers. obs.); it seems unlikely that the two peaks occur in the same months in both Maldives and southern Sri Lanka purely by chance; and this pattern of bimodal seasonality is supported by acoustic data from Chagos (Stafford *et al.*, 2011). With regard to strandings, we recognise the shortcoming of such data. Nevertheless, the broad pattern of seasonality of strandings in each area is consistent with our migration hypothesis, and cannot be explained by seasonal changes in sea conditions alone. We note in particular the Maldivian strandings (Fig. 6c), which have been recorded only during the remarkably short time period of December to February. This is the only period during which we predict that blue whales should be transiting waters upstream of the archipelago, and therefore prone to stranding. In short, the available data do support most of our predictions.

But there are exceptions: expected sightings from the western Arabian Sea during June–August and perhaps from off NE Sri Lanka during December–January are lacking, possibly due to rough weather in these locations at these times. Satellite tracking, acoustic monitoring and photo-identification (e.g. Calambokidis *et al.*, 2009), should provide means of addressing such shortfalls and further testing the migration hypothesis presented here. Furthermore, although the use of satellite derived Chl-a data as a proxy for food availability has given some useful insights into blue whale seasonality, it is a crude measure. More detailed studies of both physical and biological oceanographic processes will be needed to provide improved understanding of blue whale feeding ecology, and its impact on their seasonal distributions in the northern Indian Ocean.

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