Trends in collisions between vessels and North Pacific humpback whales (*Megaptera novaeangliae*) in Hawaiian Waters (1975–2011)

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ABSTRACT

Injury from collisions with vessels is a growing threat worldwide for many species of whales. Thirty seven years of historical records were examined for evidence of vessel collisions with humpback whales in the main Hawaiian Islands. Between 1975 and 2011, 68 collisions between vessels and whales were reported including 59 witnessed collisions and 9 observed whale injuries that were consistent with a recent vessel collision. No collisions were immediately lethal. The waters between Maui, Molokai, Lanai and Kahoolawe, which are known to have one of the highest concentrations of humpback whales in the Hawaiian Islands, had the highest incidence of collisions. Over 63% of the collisions involved calves and subadults, suggesting a greater susceptability towards collisions among younger animals. The rate of collisions increased significantly over the final twelve breeding seasons of the study and was greater than predicted by the estimated annual increase in the whale population, suggesting that the rising number of reported collisions cannot be explained solely by the annual increase in whale abundance. Although the total number of registered vessels and shipping traffic in Hawaii remained relatively constant between 2000 and 2010, there was a significant increase in the number of vessels between 7.9m and 19.8m in length. Vessels within this size range were also the most commonly involved in collisions during the study period, accounting for approximately two thirds of recorded incidents. It is concluded that from 1975–2011, there was a significant increase in reports of non-lethal collisions between vessels and humpback whales, especially calves and subadults, in the main Hawaiian Islands that likely reflects a combination of factors including the recovery of the population of North Pacific humpback whales, increases in traffic of particular vessel types, and increased reporting practices by operators of vessels.

KEYWORDS: HUMPBACK WHALE; SHIP STRIKES; STATISTICS; TRENDS; PACIFIC OCEAN; NORTHERN HEMISPHERE

INTRODUCTION

As populations of mysticete whales recover from intensive commercial hunting during the first half of the 20th century (see review in Clapham and Baker, 2009), they face a host of new anthropogenic threats. These include habitat degradation, entanglement (e.g. in fishing gear), underwater noise and collisions with vessels (Fleming and Jackson, 2011). There is mounting evidence that collisions between whales and vessels are increasing globally (Carrillo and Ritter, 2010; De Stephanis and Urquiola, 2006; Douglas *et al.*, 2008; Laist *et al.*, 2001; Panigada *et al.*, 2006). As whale and human populations continue to grow, encounters at sea between whales and vessels are becoming more frequent, sometimes with disastrous consequences for the whales, humans or both. This is notably true in areas where both human and whale concentrations are high, such as coastal urban areas in the proximity of whale feeding or breeding grounds (Carrillo and Ritter, 2010; De Stephanis and Urquiola, 2006; Panigada *et al.*, 2006; Ritter, 2010). One such location is the Hawaiian archipelago where thousands of humpback whales (*Megaptera novaeangliae*) congregate seasonally between December and April (e.g. Calambokidis *et al.*, 2008) and where in excess of eight million people reside or visit annually. This paper investigates trends in collisions between vessels and humpback whales in Hawaiian waters over a 37-year period.

The Hawaiian Islands are the principal breeding grounds for North Pacific humpback whales (Calambokidis *et al.*, 2008; Calambokidis *et al.*, 2001; Fleming and Jackson, 2011). Each year, thousands of North Pacific humpback whales migrate to Hawaiian waters, where they take up temporary residence (Craig *et al.*, 2003; Craig *et al.*, 2001). Barlow *et al.* (2011) provided a 2006 estimate of 21,808 humpback whales in the North Pacific population based on a three-year North Pacific-wide mark and recapture survey known as SPLASH (Structure of Populations, Levels of Abundance, and Status of Humpbacks). Calambokidis *et al.* (2008), using the same SPLASH data, estimated a 6% annual increase in the population of humpback whales in the North Pacific. Also, as of 2006, approximately 10,103 (55%) of the North Pacific population of humpback whales (excluding newborn calves) were estimated to visit the Hawaiian Islands (Calambokidis *et al.*, 2008).

While on their breeding grounds, humpback whales (other than newborn calves) fast and behaviour is largely related to mating and calving. Calves make up 7–9% of the Hawaii population (Mobley *et al.*, 2001). The mean age that humpback whales attain sexual maturity has been estimated at five years of age (Chittleborough, 1965; Clapham, 1992), but recent evidence suggests that it may be closer to ten in the North Pacific (Best, 2011; Gabriele *et al.*, 2007). In addition to sexually mature adults, immature whales of both sexes also migrate to Hawaii from higher latitude feeding grounds (e.g. Craig *et al.*, 2003).

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Despite their growing numbers, humpback whales are still considered an endangered species. Twentieth century commercial whaling reduced the North Pacific population to between 1,000 and 1,400 (Gambell, 1976; Johnson and Wolman, 1985; Rice, 1978). The IWC banned commercial whaling for North Pacific humpback whales in 1965. However, recent reports reveal that Soviet whaling for humpback whales actually continued until 1971 (Doroshenko, 2000). Currently, humpback whales in Hawaii (and other US waters) are protected and managed under US Federal laws including the Endangered Species Act and the Marine Mammal Protection Act, and a variety of state laws. In 1992, the US Congress designated portions of the waters of the main Hawaiian Islands as a marine sanctuary for humpback whales (Subtitle C of Public Law 102–587, the Oceans Act of 1992). In 1997, the Governor of the State of Hawaii provided approval for designated State waters to be included in the Hawaiian Islands Humpback Whale National Marine Sanctuary. Under US Federal Law, vessels other than those with a Federal Permit to conduct research or film humpback whales must remain at least 100 yards from individual humpback whales. Despite these conservation efforts and regulations, collisions between vessels and humpback whales still occur.

Several reports have been published that reviewed records of vessel collisions with humpback whales in the United States and globally (e.g. Douglas *et al.*, 2008; Jensen and Silber, 2003; Laist *et al.*, 2001; Wiley *et al.*, 1994). Wiley *et al.* (1994) examined records of humpback whale strandings along the US Atlantic coast between 1985 and 1992. They reported that 30% (6 of 20) of stranded individuals had injuries caused by vessels. Laist *et al.* (2001) conducted a study on collisions between vessels and whales worldwide, which included humpback whales. Although records revealed that vessel strikes on fin whales (*Balaenoptera physalus*) were most common, collisions with humpback whales (along with right whales (*Eubalaena glacialis*), gray whales (*Eschrichtius robustus*), and sperm whales (*Physeter macrocephalus*)) were considered relatively common.

As an island state, Hawaii is highly dependent on vessel traffic for commerce, transportation and as a major source of revenue for the local economy through the sightseeing, diving, fishing and whalewatching industries. Concurrent with the recovery of the population of North Pacific humpback whales and the growing number of humpback whales wintering in Hawaiian waters, there is growing concern about the potential for collisions (National Marine Fisheries Service, 1991). Presently, however, there is little quantitative evidence to evaluate the severity of the issue from both a conservation and safety perspective. This study provides the first empirical measure of the incidence of collisions between humpback whales and vessels in Hawaiian waters. The available historical information on the number and location of collisions over the 37-year period between 1975 and 2011 are summarised. Where available, data on vessel type and speed, as well as the age-class of whales involved in collisions are collated. The rate of collisions relative to the annual increase in whale abundance is investigated. Finally, available vessel statistics are examined to infer corollary relationships with collision trends.

METHODS

The historical occurrence of collisions between vessels and whales in Hawaiian waters was investigated by searching print media archives, government records and the scientific literature for accounts of past incidents. Print media sources included: *The Honolulu Advertiser*, *The Star Bulletin*, *West Hawaii Today*, *The Maui News*, *The Hawaii Herald Tribune*, *Hawaii Fishing News* and *The Garden Isle*. Some of these sources did not come into existence until after 1975, so their databases were searched beginning with the first archives. The government records that were examined included the 'Whale Incident Log' maintained by the National Oceanic and Atmospheric Administration's (NOAA) Hawaiian Islands Humpback Whale National Marine Sanctuary (HIHWNMS), stranding and incident records from the National Marine Fisheries Service's Pacific Islands Regional Office and information gathered via personal communication with NOAA's Office of Law Enforcement and the management staff of the HIHWNMS. Statistics on the abundance and location of registered vessels in the State of Hawaii, as well as rates of overseas and inter-island commercial ship traffic between 2000 and 2010, were obtained from *State of Hawaii Data Book* records available online from the Department of Business, Economic Development and Tourism (*http://hawaii.gov/dbedt/info/economic/databook/*).

RESULTS

Numbers of reported collisions and types of injuries

A 'collision' was defined as any physical contact occurring between a vessel and a humpback whale. No reports of collisions were found prior to 1979. From 1979–2011, there were 68 confirmed reports of collisions including 59 witnessed collisions (Table 1)[6] and 9 suspected collisions (i.e. a recent whale injury was observed consistent with a collision with a vessel but the actual collision was not reported) (Table 2). Forty-five witnessed collisions were reported as a vessel striking a whale, 12 were reported as a whale striking a vessel, and 2 were reported as both a vessel striking a whale and a whale striking a vessel (Table 1).

There were no reports of immediate whale fatalities from observed collisions. However, a dead-stranded calf found with deep, propeller-inflicted lacerations is suspected to have died from its wounds. Where injuries could be determined, the most common were lacerations for both witnessed collisions and suspected collisions. Some of these were clearly wounds from contact with a vessel's propeller (i.e. the cuts were uniform, evenly spaced, and consistent with other observations on confirmed propeller wounds). Only one confirmed case of blunt trauma was observed, with two others likely (see Tables 1 and 2).

Characteristics of vessels involved in collisions

The type of vessel was reported in 56 witnessed collisions. The majority of collisions (61%, n = 34) involved tour

[6]At least two additional incidents occurring in the late 1980s/early 1990s were reported by a humpback whale researcher on Maui in a 'Star Bulletin' article on 1 April 2002. In each case, a whale reportedly bumped the inflatable research vessel as it was operating in neutral gear. No injuries or damages were reported.

Table 1

Witnessed collisions between whales and vessels in Hawaiian waters 1979–2011.

Year	Month/day	Island	Age class	Initiator (W/V)	Injury type	V type	V length (m)	V max speed
1979	NR	Maui	NR	W	U	Research	NR	NR
1981	Feb. 02	Hawaii	Adult	W	U	Tour	NR	7
1987	Jan. 01	Hawaii	NR	V	L	Dive	9.1	15
1988	Mar. 26	Maui	Adult	V	U	NR	7.3	26
1990	Mar. 01	Hawaii	Adult	V	U	Fishing	5.8	NR
1995	Feb. 22	Maui	Adult*	V	L	Tour	19.8	NR
1996	Jan. 16	Maui	Adult	V	U	Tour	25	8
1998	Jan. 01	Maui	NR	V	U	Tour	25	NR
1998	Mar. 30	Oahu	Adult	V	BT	Mil/Gov	91.4	8
2000	Feb. 04	Oahu	NR	V	U	Fishing	6.1	8
2001	Feb. 01	Maui	U	V	L	Tour	NR	18
2001	Feb. 15	Kauai	Juvenile	W	U	Tour	12.2	NR
2002	Mar. 01	Maui	Adult	W	U	NR	NR	0
2002	Mar. 15	Maui	Adult	W	L	Tour	19.8	NR
2002	Mar. 27	Maui	Calf	V	U	NR	NR	NR
2003	Feb. 10	Maui	Juvenile	V	U	Tour	19.8	NR
2003	Feb. 16	Kauai	NR	V	U	Cargo	91.4	NR
2003	Mar. 07	Maui	NR	V	U	Tour	NR	17
2003	Dec. 25	Oahu	Adult	V	U	Tour	32.9	NR
2004	Jan. 05	Maui	NR	V	U	Fishing	5.5	NR
2004	Feb. 08	Maui	Calf	V	U	Pleas/Priv	6.7	NR
2005	Feb. 06	Lanai	Calf	V	U	Ferry	45.4	17.4
2005	Feb. 21	Oahu	NR	V	U	Fishing	NR	NR
2005	Feb. 25	Oahu	NR	V	U	Sailboat	NR	NR
2006	Jan. 04	Maui	NR	V	U	Tour	NR	13
2006	Jan. 17	Kauai	NR	V	U	Tour	18.3	15
2006	Feb. 13	Maui	NR	V	U	Mil/Gov	7.6	10
2006	Mar. 09	Maui	Calf	V	L	Tour	19.8	15
2006	Mar. 25	Maui	U**	V	U	Tour	9.8	22
2006	Dec. 28	Kauai	NR	V	U	Tour	NR	15
2007	Feb. 07	Maui	U	V	L	Ferry	19.8	20
2007	Mar. 08	Maui	Juvenile	W	U	Tour	9.1	0
2007	Apr. 01	Kauai	Juvenile	V	U	Tour	19.8	10
2007	Apr. 13	Lanai	Calf	V	L	Tour	15.5	18
2008	Jan. 10	Hawaii	Adult	V	U	Tour	9.1	13
2008	Jan. 27	Oahu	Calf	V	U	Tour	13.41	6
2008	Feb. 05	Maui	Juvenile	V	U	Research	10.36	8
2008	Feb. 27	Oahu	Adult	W	U	Mil/Gov	NR	NR
2008	Feb. 28	Maui	Juvenile	V	L	Tour	19.81	12.5
2008	Mar. 04	Hawaii	Calf	V	L	Tour	8.84	13
2008	Mar. 05	Maui	Adult*	V	U	Tour	19.81	NR
2008	Mar. 21	Hawaii	Adult	W	U	Tour	NR	NR
2008	Mar. 27	Lanai	Calf	V	U	Tour	9.14	19
2009	Feb. 05	Maui	Adult	V	L	Ferry	19.8	NR
2009	Feb. 21	Maui	Calf	V	U	Tour	15.24	8
2009	Feb. 27	Maui	Adult	W	U	Research	8.53	1
2009	Mar. 01	Maui	Calf	W	U	Tour	19.81	0
2009	Mar. 22	Hawaii	Juvenile	V	U	Tour	7.32	20
2009	Mar. 23	Maui	Calf	V and W	U	Other	4.57	10
2009	Mar. 27	Maui	Adult	W	U	Research	10.36	5
2009	Mar. 29	Maui	Juvenile	V and W	U	Other	4.57	NR
2009	Dec. 08	Maui	Juvenile	V	U	Tour	9.14	25
2010	Jan. 08	Maui	Juvenile	V	U	Tour	19.81	13
2010	Feb. 14	Hawaii	Adult	V	U	Tour	9.75	10
2010	Feb. 23	Hawaii	Calf	V	U	Tour	19.81	10
2011	Feb. 15	Maui	Calf	V	U	Tour	19.81	15
2011	Feb. 16	Maui	Mother and Calf	V	L	Fishing	9.45	NR
2011	Feb. 21	Oahu	Juvenile	V	U	Mil/Gov	7.62	26
2011	Mar. 08	Maui	Adult	W	U	Tour	16.76	4

*Mother-calf pair (mother struck). **Mother-calf pair (unknown whether one or both whales struck). Mi = military vessel, Gov = government vessel, Pleas = pleasure boat, Priv = private boat. L = laceration, BT = blunt trauma, NR = not reported, U = unknown, W = whale, V = vessel.

vessels (e.g. whalewatching, diving, snorkelling; Fig. 1). Vessel length was determined in 47 witnessed collisions (Mean = 17.78m, SD = 17.59m, Range = 4.57m–91.4m). 87 percent of collisions involved vessels whose lengths were ≤ 21.2m (Fig. 2). The speeds of vessels involved in collisions were reported in 39 incidents. Mean reported maximum vessel speed at the time of the collision was 12.33 kts (SD = 6.96 kts, Range = 0–26.1 kts) (Fig. 3). The majority of vessels involved in a collision (51%) had maximum reported speeds of between 10 and 19 knots.

Location and timing of collisions

Witnessed collisions were not distributed equally among island regions (Fig. 4; χ^2 (3) = 45.3, $p < 0.001$). The majority

Table 2

Suspected collisions between whales and vessels in Hawaiian waters 1979–2011.

Year	Month/day	Island	Age class	Injury type
1994	Feb. 10	Maui	NR	L
1996	Jan. 18	Oahu	Calf	L
1996	Jan. 22	Maui	Calf	L
1999	Mar. 25	Maui	Calf	L
2005	Feb. 28	Maui	Calf	L
2006	Mar. 15	Maui	Calf	U
2006	Dec. 29	Maui	Calf	L
2008	16. Apr	Maui	Calf	L
2010	Feb. 28	Hawaii	Calf	U

L = laceration, U = unknown.

(*n* = 37) of collisions were in the Maui Nui Region (i.e. the channels between Maui, Lanai, Kahoolawe, and Molokai) while the fewest number (*n* = 5) occurred off Kauai. Fig. 5 shows the percentage of witnessed collisions occurring per month. The two months with the highest incidents of collisions were February and March.

Age class of whales involved in collisions

The age class of a humpback whale involved in a vessel collision (witnessed and suspected combined) was reported in 52 cases. Calves and juveniles combined had a greater incidence of reported vessel collisions (63.5%) than did adults (36.5%) (χ^2 (1) = 3.77, p = 0.05), (Fig. 6). In the Maui Nui region, of 29 collisions in which the age class of the whale was reported, 62% involved either a calf or a juvenile.

Temporal trends in collisions

Fig. 7 shows the number of reported collisions (witnessed and suspected combined) per year across six 6-year binned calving seasons from 1976–2011. There was a 20-fold significant increase in the annual incidence of reported collisions over this period (r^2 = 0.74, f (1,4) = 11.22, p = 0.03). To examine if the rate of collisions relative to whale abundance remained constant over time, a mean whale abundance estimate for each 6-year binned calving season was calculated by taking the 2006 whale abundance estimate for the Hawaiian Islands of 10,103 whales provided by Calambokidis *et al.* (2008) and extrapolating using an estimated annual increase in whale abundance of 6% (Calambokidis *et al.*, 2008) and an estimated 9% of the Hawaii population of humpback whales being composed of calves (Mobley *et al.*, 2001). There was a significant increase in the number of collisions per mean number of whales across binned periods (r^2 = 0.69, f(1,4) = 8.69, p = 0.04). Thus, the rate of whale collisions relative to whale abundance did not remain constant across years but instead increased. Furthermore, when we controlled statistically for the estimated annual increase in whale abundance, the increasing number of collisions per year remained significant (standardised regression coefficient β = –1.09, t = –5.35, p = 0.01). In summary, the increase in number of collisions over time could not be attributed solely to greater estimated whale abundance. This increase in collisions was also present when considering only the most recent 12-year period (2000–11). There was a significant increase in the mean number of collisions adjusted for estimated annual whale abundance between the periods from 2000–05 (mean = 2.92×10^{-4}) and 2006–11 (mean = 5.18×10^{-4}) (t(10) = 2.64, p = 0.025).

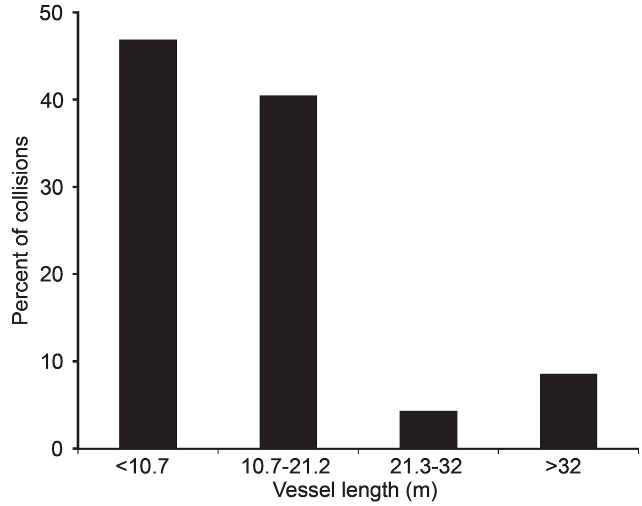

Fig. 2. Percentage of witnessed collisions between humpback whales and vessels in Hawaiian waters from 1975–2011 involving vessels of various lengths (*n* = 47 reports).

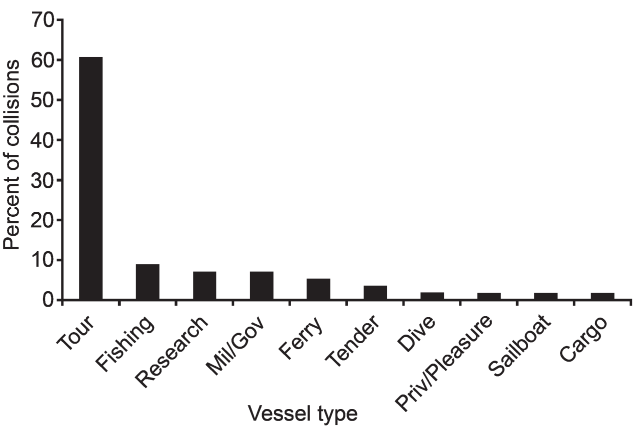

Fig. 1. Percentage of witnesssed collisions between humpback whales and vessels in Hawaiian waters from 1975–2011 as a function of vessel type (*n* = 56 reports).

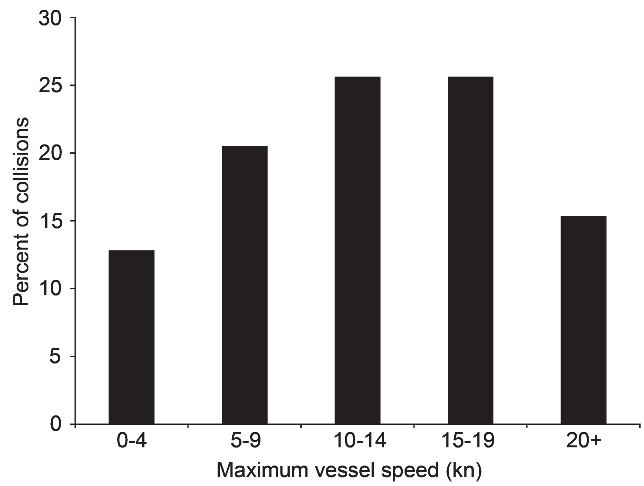

Fig. 3. Percentage of witnessed collisions between humpback whales and vessels in Hawaiian waters from 1975–2011 involving vessels traveling at various maximum speeds (*n* = 39 reports).

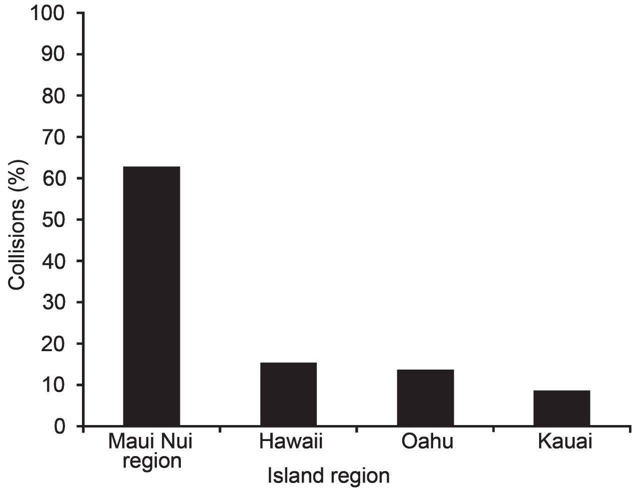

Fig. 4. Percentage of witnessed collisions between humpback whales and vessels in Hawaiian waters from 1975–2011 off each island region (n = 58 reports).

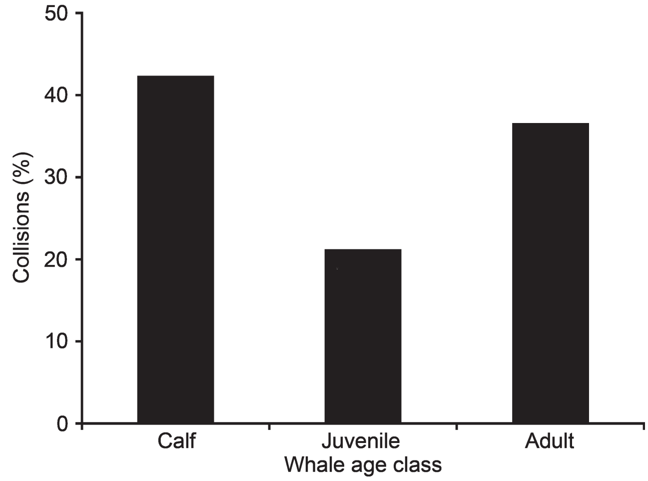

Fig. 6. Percentage of humpback whales of reported age classes involved in vessel collisions (witnessed and suspected combined) in Hawaiian waters 1975–2011 (n = 52 reports).

State of Hawaii vessel registrations and shipping traffic between 2000–2010

Table 3 shows the data for annual vessel registrations by size class and by island, as well as ship arrivals at Honolulu harbour from overseas and inter-island traffic. Only Hawaii Island experienced a significant increase in the mean number of vessel registrations from 2000–2005 (Mean = 2512.33, SD = 135.84) versus 2006–10 (Mean = 2,676.60, SD = 119.92) (one-tailed t test, t((9) = 2.10, $p < 0.05$). The other island regions experienced no significant increase in mean vessel registrations from 2000–2005 versus 2006–10. Overseas shipping traffic showed a significant decrease from 2000–05 (Mean = 1213.33 arrivals, SD = 81.26 arrivals) versus 2006–10 (Mean arrivals = 983.40 arrivals, SD = 68.29 arrivals) ($t(9) = 5.01$, $p < 0.001$) while inter-island traffic remained unchanged.

Fig. 8 shows annual trends in vessel registrations in Hawaiian waters from 2000–10 for vessels of various lengths with the abundance of each year normalised to the maximum for the 11-year period. A regression analysis revealed only two significant positive linear correlations between year and normalised vessel abundance: for vessels 7.9–12.2m (r^2 = 0.85, $f(1,9) = 52.30$, $p < 0.001$; and for vessels 12.2–19.8m (r^2 = 0.65, F (1,9) = 17.01, p = 0.003). The difference between the mean abundance of vessels of different size from 2000–05 versus 2006–10 was also tested. A one-tailed t test revealed that the only significant increases in abundance between the two periods were for vessels 7.9–12.2m ($t(9) = 4.31$, p < 0.01) and 12.2–19.8m ($t(9) = 2.17$, $p < 0.05$).

DISCUSSION

Historical trends

Although the number of whale/vessel collisions varies from year to year, there is compelling evidence that the rate of incidents is on the rise in Hawaiian waters. Perhaps most telling are the data showing an increase during the two most recent six-year periods (2000–05 and 2006–11). Because this comparison excludes data from earlier years when more incidents may have gone unobserved and/or unreported (e.g. due to a lack of formal reporting mechanisms or possibly a reluctance of some vessel operators to report incidents), it

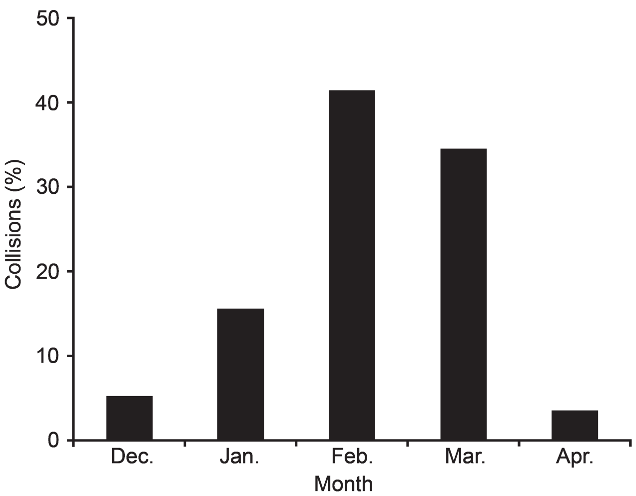

Fig. 5. Percentage of witnessed collisions between humpback whales and vessels in Hawaiian waters from 1975–2011 occurring per month (n = 58 reports).

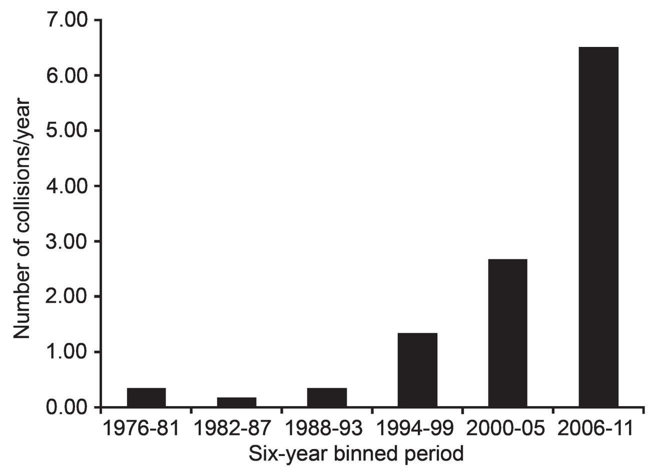

Fig. 7. The number of reported collisions between humpback whales and vessels in Hawaiian waters (witnessed and suspected combined) per year across six 6-year binned calving seasons from 1976–2011.

Table 3

Annual vessel registrations by size class and by island and ship arrivals at Honolulu harbour from overseas and from inter-island traffic between 2000 and 2010.

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Length (m)											
< 4.9	5,680	5,370	5949	5,827	6,533	5,940	5,770	5,695	6,424	5,842	5,343
4.9 < 7.9	7,476	7,248	7698	7,918	8,772	7,367	7,420	7,443	8,138	7,762	7,455
7.9 < 12.2	1,537	1,483	1596	1,632	1,616	1,695	1,701	1,736	1,914	1,860	1,804
12.2 < 19.9	169	166	187	193	191	251	209	211	256	231	229
> 19.9	12	6	15	17	18	49	9	9	12	14	16
Total	14,874	14,273	15445	15,587	17,130	15,302	15,109	15,094	16,744	15,709	14,847
Location											
Hawaii	2,420	2,328	2519	2,521	2,731	2,555	2,650	2,632	2,876	2,671	2,554
Kauai	1,728	1,647	1748	1,604	1,713	1,585	1,580	1,539	1,718	1,647	1,564
Maui Nui	1,882	1,777	2146	2,017	2,410	2,121	2,041	2,042	2,326	2,170	2,007
Oahu	8,829	8,543	9032	9,445	9,251	8,016	8,791	8,881	9,824	9,221	8,722
NS	N/A	N/A	N/A	N/A	1,025	1,025	47	N/A	N/A	N/A	N/A
Honolulu arrivals											
Overseas	1,292	1,295	1270	1,169	1,133	1,121	1,061	1,027	1,002	931	896
Inter-island	2,215	2,280	2663	2,521	2,418	2,580	2,972	3,157	2,964	2,512	2,264

is probably a more accurate assessment of the trend in collisions.

Approximately 75% of reported collisions occurred during either February or March, which coincides with the seasonal peak of whale abundance in Hawaii (see Baker and Herman, 1984; also summarised in Mobley *et al.*, 1999). This indicates that a relationship exists between whale density and the frequency of collisions. However, it was found that on an annual basis the higher number of reported collisions could not be solely accounted for by the estimated annual increase in whale abundance in Hawaii. This suggests that either higher vessel traffic and/or the behaviour of vessels around whales also play a role in the rate of collisions. Although the total number of registered vessels and shipping traffic in Hawaii remained relatively constant between 2000 and 2010, there was a significant increase in the number of vessels between 7.9m and 19.8m in length. In other words, there was a correspondence between the number of vessels of this size class operating in Hawaii and the rate of collisions with whales. Coincidentally, vessels within this size range were also the most commonly implicated in collisions during the study period, accounting for approximately two thirds of recorded incidents.

The majority of reported incidents occurred in waters in the Maui Nui region, a relatively shallow (< 200m depth) area with one of the densest aggregations of humpback whales in the Hawaiian Islands. This is also an area of high vessel concentration, especially during whalewatching months. The majority of incidences over the past five years in which the vessel type was specified involved commercial whalewatching vessels. This could simply reflect a greater likelihood that a collision with a whalewatching vessel carrying passengers will be reported. Alternatively, it may indicate that tour vessels that regularly operate in whale-dense areas or in the proximity of whales, and specifically seek out whales for close approach and observation, may be more prone to collisions.

Collision characteristics

Laist *et al.* (2001) noted that vessel collisions with whales generally result in two types of injuries; propeller wounds and blunt trauma. Both types were evident in our database,

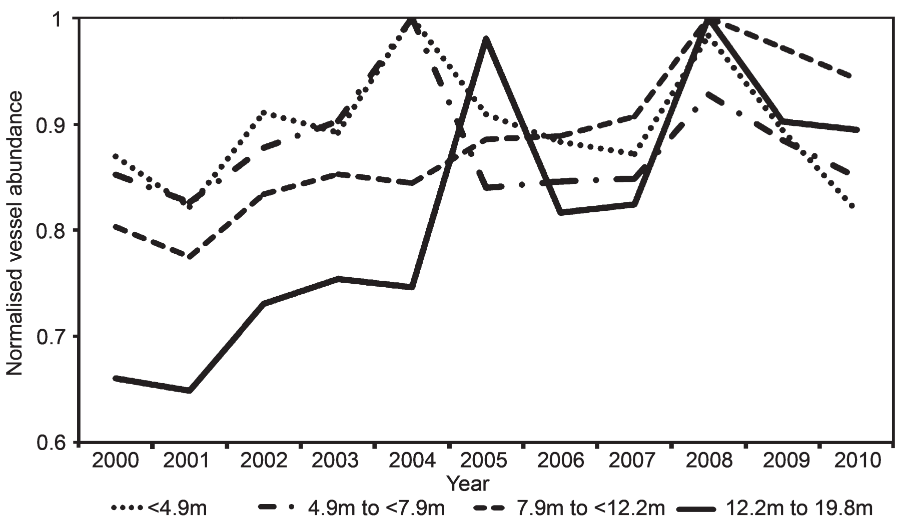

Fig. 8. Annual trends in vessel registrations in Hawaiian waters from 2000–10 for vessels of various lengths with the abundance of each year normalised to the maximum for the 11-year period.

though lacerations were much more prevalent. Only one instance of a suspected vessel collision-related mortality was recorded; a dead-stranded calf with deep propeller wounds on the island of Oahu. However, in several other incidences where deep wounds were observed on living calves, as well as the adult observed with blunt trauma, the whale's survival was considered dubious.

The data compiled by Laist *et al.* (2001) indicated that calves and juveniles on the feeding grounds or along a migration route were highly vulnerable to collisions with vessels. A parallel situation is seen for the Hawaiian wintering grounds. For humpback whales in Hawaiian waters, over half of the incidents in which the age class of the whale was specified involved either a calf or a juvenile. This may not be surprising as calves spend more time at the surface to breathe than adults, will often surface without the mother if the pod is stationary, are less visible than adults, and are relatively naïve to interactions with vessels (Glockner and Venus, 1983). Silber *et al.* (2010) showed that whales submerged by only one or two times a vessel's draft, which is typical for calves, experience a pronounced propeller suction effect, drawing them toward the hull, and thereby increasing the probability of a propeller strike.

Vessel speed does appear to play a role in collisions in Hawaiian waters. The majority of incidents (where maximum speed was reported) were with vessels having top speeds of 10–19 knots. This trend is consistent with findings by Gende *et al.* (2011) who examined the role of vessel speed in whale/ship encounters and found that the relationship between whale distance and ships changes at 11.8 knots (6.1 m s^{-1}), with whales encountering ships at significantly closer range, on average, when the ship's speed is above 11.8 knots. Vanderlaan and Taggart (2007) similarly found that the probability of a lethal injury to North Atlantic right whales (*Eubalaena glacialis*) is greater than 0.5 at collision speeds above 11.8 knots, while Silber *et al.* (2010) also found that factors affecting the severity of injury are tied to vessel speed. These lines of evidence suggest that above speeds of approximately 12 knots whales may have more difficulty avoiding a close encounter with a vessel and that collisions above this speed have a greater likelihood of injury or death.

The extent of injuries suffered from collisions by whales is a difficult variable to quantify. Laist *et al.* (2001) indicated that trauma suffered from collisions among stranded whales is often not apparent unless a thorough necropsy is performed and the integrity of the bones is examined by flensing through the blubber. Lacerations resulting from propeller cuts are the more obvious form of injury observable, but perhaps not necessarily the most common type. Blunt trauma such as fractures and internal bleeding are more difficult to establish and probably go unnoticed more often. Therefore, although several of the reports described suggested that no injuries were sustained, these assessments were likely biased by the inability to observe blunt trauma injuries.

Finally, no cases of whale carcasses pinned to the bow of ships were reported in Hawaii during the period examined. This is in contrast to the findings of Laist *et al.* (2001) for whom such cases comprised a significant component of the database. In Hawaii, it appears the majority of vessels involved in collisions are small to medium sized boats less than 21.2m in length. The lack of incidents reported involving large ships is somewhat curious, but perhaps indicates that presently established shipping lanes are not a major problem in this regard. However, a more thorough assessment of this assumption is clearly warranted, as alternate explanations such as under-reporting are also possible.

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