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Ship's compliance with a traffic separation scheme and speed limit in the Gulf of Panama and implications for the risk to humpback whales

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ABSTRACT

To reduce the whale-vessel strike risk in the Gulf of Panama, the International Maritime Organization (IMO) adopted a Traffic Separation Scheme (TSS) with corresponding inshore traffic zones and seasonal (Aug–Nov) speed limits of ≤10 kn (Speed Over Ground, SOG) commencing December 2014. Here, we assessed compliance rates to these new regulations. Vessel traffic data in the area were obtained between 2014 (pre-TSS implementation) and 2016 using Automated Identification System (AIS) transponders. Most vessels (86.1 and 89.8% in 2015 and 2016, respectively) promptly adhered to the TSS. Significant differences were also detected in speed compliance rates among years, but overall speed compliance was low, i.e., only 19.0% of ships in 2015 and 9.7% in 2016 traveled at ≤10 kn. Compliance rates with the TSS and speed limits varied significantly by vessel type. These divergent compliance responses were likely due to inadequate communication to mariners and notes on printed and digital charts. Speed compliance could be enhanced, e.g. via education programs to raise awareness of endangered whales, along with collaborative initiatives between the maritime industry and port authorities, and law enforcement. In addition, continued monitoring of compliance with IMO regulations, as well as ship-related cetacean injuries/mortality by local environmental authorities should aid assessing the efficacy of these conservation measures and mitigating the whale-vessel strike risk in the Gulf of Panama. Above all though, authorities need to evaluate a mandatory speed regulation by the IMO or unilaterally, based on the newly modified and extended baseline for nation's internal waters.

1. Introduction

Transiting vessels can cause serious damage and lethal injuries to marine megafauna through vessel collisions [1–4]. Particularly large cetaceans such as fin whales (*Balaenoptera physalus*) [5], Northern and Southern right whales (*Eubaelena glacialis*) [6], blue whales (*Balaenoptera musculus*) [7], and humpback whales (*Megaptera novaeangliae*) [8–11], which are at higher risk of being hit by a vessel, but also smaller species, including turtles, pinnipeds and manatees, are affected [1,2,4]. Ship strikes represent among the most serious anthropogenic threats to whale populations, especially if these jeopardize viability of a population and thus long-term survival or recovery [9,10,12].

Reports of fatal ship strikes date back to the late 19th century and over the past 25 years have been increasing with the growing number as well as increasing size and speed of vessels [9,13]. Although not restricted to one type or size of ship, impacts caused by larger vessels (>80 m) and those moving with high velocity (>14 kn) are more detrimental and often lethal to struck whales [9,14,15]. As per April 2008, more than 750 ship strikes against large whales have been reported according to the International Whaling Commission (IWC) Ship Strike database [16]. Yet, it is assumed that the actual number is much higher, as most incidents remain unnoticed and/or unreported [10], for example, due to advanced decomposition or absence of external injuries following the vessel strike coupled with a lack of internal examination of whale carcasses [8–10]. Furthermore, most lethally struck animals that die do not strand in general [3].

High Risk Areas (HRA), as defined by the IWC [12], that exhibit high levels of shipping traffic alongside dense aggregations of whales (e.g., feeding and breeding grounds) such as Spain [17], the Mediterranean [5], United States [18], Canada [19], Chile [20] and Panama [11], result in high probability for whale-ship collisions [10]. However, with growing conservation efforts, coastal states have implemented and

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amended mitigation routeing measures to reduce the possibility of ship-whale collisions in HRA, which include, for instance, mandatory or voluntary ship speed restrictions [11,15,21–23] Traffic Separation Schemes (TSS) [10,11,24], Areas to be Avoided (ATBAs) [10,25,26], a Mandatory Ship Reporting System (MSRS) [10] as well as increased monitoring efforts and data collection [27]. Furthermore, progress has been made towards developing near real-time identification [28,29] and navigational software to prevent whale collisions [15]. In particular, the International Maritime Organization (IMO), as the main United Nations (UN) body to ensure maritime safety and marine environmental protection, plays a central role in adopting codes and recommendations to regulate maritime traffic in both national and international waters [10]. Under the Safety of Life at Sea (SOLAS) convention (regulation V/19.2.4), the IMO mandates AIS (Automated Identification System) transponders on all larger vessels (>300 GT) and all passenger vessels sailing in international waters, which enables remote assessment of the

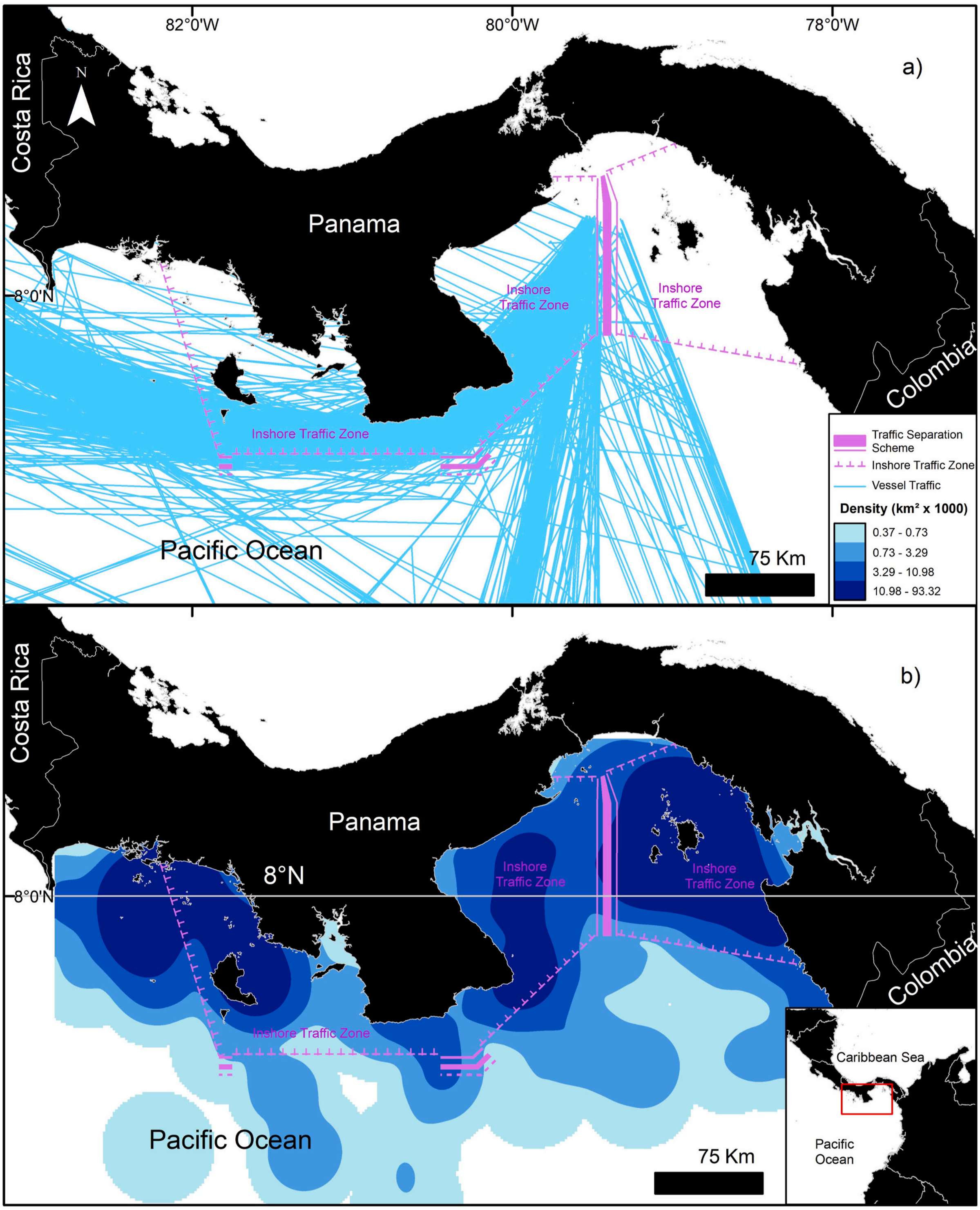

Fig. 1. Gulf of Panama study area showing maritime traffic during 2013 (blue tracks), and position of the Gulf of Panama TSS networked (magenta) with two other ones (lower left), as implemented on Dec. 1st, 2014, including inbound and outbound lanes, the ca. 37,815 km^2 inshore traffic zones, and the parallel 8°N speed limit line (a), and kernel density distribution of humpback whales along Pacific Panama (b).

ship's position, speed and heading, but also compliance with conservation measures [25,30,31,56].

Globally, reports on fatal whale-vessel collisions have been biased towards certain areas in the Northern Hemisphere, including the North Pacific, North Atlantic and Mediterranean, while there have been limited records from mid- and southern latitudes, including Central and South America [3]. The Panama Canal makes the Isthmus of Panama, and adjacent waters, a major transit hub for international shipping [32]. At the same time the Gulf of Panama displays an important wintering ground for migrating humpback whales resulting in high risk of vessel strikes [11,33,34]. Only few years ago, Panama began to collate data on cetacean mortality associated with vessel strikes, which already comprised 13 incidents recorded between 2009 and 2011 [11].

The recent expansion of the Panama Canal, inaugurated on June 26th, 2016, now also allows transit of large Neo-Panamax (i.e., 5000–12,000 twenty-foot equivalent containers [TEU]) vessels [32,35] and thus the number of ships surpassing the canal could further increase [32]. In 2018, the Panama Canal conducted 12,199 transits, where 79.6% of the vessels consisted of Oceangoing Commercial Traffic, such as cargo ships, tankers, and container ships, while 20.4% transited Neo-Panamax locks [35] The Gulf of Panama experiences a constant flux of large vessels, 24 h, each day, year-round [36] that reach average speeds of 15–17 kn and thus increase the probability of severe injury or fatalities of cetaceans [11].

Coastal waters off Pacific Costa Rica and Panama represent the only confirmed place with overlapping humpback whale populations from both hemispheres along the eastern Pacific [33,34]. Both countries recently adopted IMO's routeing systems, TSSs in Panama [37] and ATBAs in Costa Rica [38]. During austral and boreal winter, humpback whales migrate from high northern and southern latitudes to Central America for breeding and calving [33,34,39–41]. Due to the inability of the calf to conduct long dives, mother-calf pairs tend to spend the majority of their time in shallow waters (<20 m) exposing them to threats, such as whale-vessel collisions [41,42]. Furthermore, owing to their small size, calves are often overlooked and also less experienced towards boats than adults, thus showing attraction to rather than avoidance of vessels [43]. Unsurprisingly, calves, juveniles and newborns comprise a large fraction of whale individuals struck by vessels [9,43,44].

To minimize the likelihood of whale-vessel encounters, the IMO adopted a three-TSS system from December 1, 2014 accompanied by two large inshore traffic zones (ITZ) along with a recommended seasonal speed limits (<10 kn speed over ground [SOG] between August and November each year) for Pacific Panama (Fig. 1a). Compliance to the TSS was expected to reduce the number of whale vessel strikes by more than 90% [11].

To appraise the effectiveness of management actions, such as mandatory TSS routeing systems and recommended or voluntary speed reductions, requires constant assessment and reevaluation, including mariner compliance to new regulations and achievement of conservation goals (as in decrease in lethal vessel-whale encounters over time) [45]. In this study, ship compliance within the Gulf of Panama TSS and associated speed restrictions are assessed. AIS datasets are used to track vessels' geographic position and movement and furthermore monitor ship speed during and outside the four months of whale season.

2. Material & methods

2.1. Description of the study area

The Gulf of Panama is a semi-circular embayment bounded by the Isthmus of Panama in the north and open to the Pacific Ocean in the south, encompassing an area of 28,800 km^2 measured at the entrance from Punta Mala to Punta Jaque. The gulf has a maximum east-west width of 205 km narrowing towards the inner section, 175 km north-south length, and average depth of 60 m within the maximum 200 m depth isobath at the entrance [46]. The Gulf of Panama is seasonally affected by the wind jet upwelling-induced from Northeast (Trade Winds) during the dry season (generally January–April) that weaken and disappear in late April–May, and towards the rainy season dominated by the doldrums or calm winds and the onshore southeastern Pacific winds [46,47]. Tide currents are semi-diurnal with four daily cycles of 6 h, affected seasonally as well showing low sea-level conditions during the rainy season [47]. The surface circulation pattern inside the Gulf of Panama is described as counterclockwise throughout the year with average velocities of 30–40 cm/s during the dry season and decreasing thereafter to 20–30 cm/s. However, a strong southwesterly outflow current is upheld of 30–40 cm/s within the innermost region of the gulf, west from Las Perlas Archipelago and decreasing toward Punta Mala [see Ref. [46,48,49].

2.2. IMO adopted routeing systems

The Panama Maritime Authority (PMA) officially presented two proposals for the IMO 59th session of the Sub-Committee on Safety and Navigation in September 2013. IMO officially adopted the proposals in May 23, 2014 at the 93rd meeting of the Maritime Safety Committee, in accordance with the resolution A.858 (20), for the following new traffic separation schemes: "On the Pacific coast of Panama" and "At the approaches to Puerto Cristobal" on the Caribbean side. Among the most important considerations for maritime traffic and the marine environment forwarded by the PMA included: the existence of 11 marine sensitive ecosystems, a winter breeding area for humpback whales in the Gulf of Panama, and the existence of coastal artisanal and recreational fisheries for the Pacific side of the isthmus, and three sensitive ecosystems in the Caribbean. The existence of the migratory route and breeding site for humpbacks only occurs in the Pacific. Additional protection for whales along the coast was obtained by adopting two large ITZs to the east (ca. 13,447 km^2) and west (ca. 24,367 km^2) of the TSS [37], which are equivalent to other navigational-restricted routeing system like ATBAs [*sensu* [21].

A three-TSS system in Pacific Panama (Fig. 1a) became effective of December 1, 2014. The most important routeing scheme of which, in the Gulf of Panama, has a total length of ca. 111.5 km (60.2 nmi) [37]. Additionally, recommended and seasonal speed restrictions apply for inbound and outbound vessels between August and November, i.e. the peak of the humpback whale breeding season, to reduce their speed to 10 kn as they traverse parts of the TSS from 8°N to the north [50], clearly stated as "In order to help reduce the risk of lethal strikes with cetaceans, it is recommended that, as far as it is safe and practical to do so, ships should proceed at a speed of not more than 10 knots from 1 August to 30 November every year. This recommendation applies to both traffic lanes of the Traffic Separation Scheme in the Gulf of Panama, north of latitude 08°00'.00 N".

2.3. Data origin and processing

Similar to Silber et al. [23], this study analyzed AIS data that uses very high frequency (VHF) vessel transmissions to monitor vessel compliance and demographics. All individual vessels delivered one transmission every several minutes providing static (vessel characteristics) and dynamic parameters such as time, speed, course, and geographical locations at that instant [19,28]. Data were obtained from Vessel Finder Ltd's terrestrial AIS stations at 5-min time resolution, including 1,142,901 transmission records between November 1, 2013 and December 31, 2016. Data from November 2013–November 2014 represented the control as it includes pre-TSS vessel transmissions and will be considered 2014 throughout the study. Data from December 2014–December 2015 and January 2016–December 2016 represented the experimental group as it includes post-TSS vessel transmissions and will be considered 2015 and 2016, respectively, throughout the study. All transmissions from 2014, 2015, and 2016 originated from within a defined maximum and minimum geographic boundary

(08.80000–07.41667 N; 078.91667–080.00000 W, Fig. 1a) area.

The IMO Identification (ID) number is a unique seven-digit number assigned to the vessel, regardless of change of ownership, name or flag, which was implemented in 1987 and made mandatory in 1996 for vessels >300 gross tons and since 2013 has been becoming voluntary for fishing vessels >100 gross tons [30,51,52]. For this reason, unique vessel and their transits were identified by their respective IMO identification number.

The AIS ship type number is a two-digit number method of categorization representing the vessel-type of each vessel and is entered manually by the vessel's crew. This study arbitrarily used the vessel's AIS ship type number to identify the general categories of the five vessel types the analyses were focusing on: Fishing Vessel (30), Pilot Vessel (50–59), Passenger Vessel (60–69), Cargo Vessels (70–79), and Tanker Vessels (80–89) [53]. AIS ship types #31–39 (incl., tug, dredger and sailing boats) were summarized as "Others".

Individual transits were either considered an inbound or outbound movement within the geographic boundary. Most vessels within the geographic boundary conducted more than one transit per year and, in some cases, more than one transit per day. To account for multiple transits, individual transits were established by the Time Stamp and Course according to each transmission. With regards to Time Stamps, a transit had to be conducted in less than 24 h. For transits Course, provided by the AIS transmissions, specified compass movements where $\leq 90^\circ$ or $>270^\circ$ was determined as northern-bound/inbound trips and $>90^\circ$ and $<270.0^\circ$ was determined as southern-bound/outbound trips of each vessel. Combining Time Stamps with Course per vessel, individual transits within a 24-h period could be determined by individual inbound and outbound transits or with transits separated by more than 24 h traveling in the same direction.

In addition, traffic density maps were made by FleetMon (www.fleetmon.com) based on 14,104,762 transmission records between January 1, 2014 and December 31, 2016 and for a larger area including all three adopted TSS in Pacific Panama.

2.4. Identification and correction of errors

AIS data offers a detailed compilation of information which occasionally is received with errors [30]. This study identified and corrected errors in data which directly affected analyses pertaining to the aims of this study. In line with Silber & Bettridge [30], we argue though that most of the AIS data is accurate and that potential problems are overcome by statistical insignificance due to the large representative amount of data.

When representing vessels with their IMO ID number, a few cases presented the IMO ID as zero. To amend the error, the MMSI (Maritime Mobile Service Identity) identification number was used to retrieve information from the Web (http://marinetraffic.com) to help identify the vessel and locate its respective IMO ID number. The MMSI code is a unique nine-digit number regulated by the International Telecommunications Union (ITU) assigned to the AIS unit. In the few cases where transmissions did not supply critical identification information such as IMO and MMSI ID numbers, name, call sign, size and AIStype description, the vessel and their respective transmissions were completely excluded from the analyses.

After careful observation, AIS ship type numbers: 0, 1–19, 38, 39, and 90–99 yielded no or ambiguous vessel descriptions such as "Unspecified" or "Other". In all cases that did so, the vessel was evidently mislabeled by the vessel's crew or responsible officer. This problem also arose with Silber and Bettridge [30]. To amend the error, internet searches (http://marinetraffic.com) with the IMO ID yielded a vessel description and image that were cross-referenced with the AIS type guide to generate a new updated and representative AIS ship type number only for vessels exhibiting ambiguous AIS ship type numbers.

2.5. TSS compliance

Nautical chart displaying the TSS [54] was used as geographic calibration on ArcGIS (10.6) using the ArcMAP Tracking Analyst Tool and Query Builder Dialog Box [55] to assure the AIS data tracking points were as accurate as possible. Then, AIS data vessel tracking points were plotted against the calibrated nautical chart. A transit was considered compliant if the vessel remained within the TSS boundaries at all times. However, to account for transits where vessel operators modified their behavior but still crossed TSS limits an additional buffer zone surrounding the TSS was added. The buffer zone consisted of a 1.25 nm^2 area (2.5 nm $\times$ 0.5 nm) on the West and East side of the TSS at the extremity closest to the Canal's anchoring area and a 0.2 nm extension from the original TSS limit along all the TSS borders. Transits undertaken within TSS limits at all times were considered as strictly Compliant. Transits within the buffer zone were considered as Non-compliant. Transits where at least one AIS data tracking point was found outside the TSS limit and buffer zone were considered as Non-compliant.

2.6. Speed limit compliance

AIS data vessel tracking points were filtered for the months where the 10 kn speed restriction is in effect, i.e. August, September, October, and November for each year [50]. To calculate an accurate value of average speed for the AIS data tracking points, data points with speeds less than or equal to 2 kn and above the 8° latitude line were removed from the calculations to eliminate any vessel that was potentially anchored and generating many AIS tracking points with speed = 0 kn skewing the average to a lesser value. In addition, any transits with speeds surpassing 30 kn were eliminated, since these likely represent erroneous measurements. This also resulted in fewer transits being available to assess compliance with speed limits compared to spatial data (TSS). With the remaining AIS tracking points, speed averages were taken per AIS type category per year. AIS data indicate the ship's speed as SOG. To take into account vessels that may follow STW (Speed Through Water) limits, minimum and maximum water flow velocities (20–40 cm/s) were included to calculate the difference between SOG and STW.

2.7. Whale density distribution

Twenty-nine satellite transmitters were deployed on humpback whales, 24 in Panama between 2009 and 2014 and five in southern Costa Rica in 2015. Wildlife Computers SPOT5 tag models (AM-S193) were used. Only 20 tags transmitted reliable coordinates inside Panamanian waters and were used for density analysis. A detailed description of the tagging procedure is provided elsewhere [34,41]. The Animal Care and Use Committee of the Smithsonian Tropical Research Institute approved the tagging procedure.

2.8. Statistical analysis

Chi-square analyses were computed using SigmaPlot 12.5 to compare mariners' compliance rates to TSS and ship speed limits among years (before and after implementation) and vessel type (post implementation). To evaluate if compliance to ship speed reductions was independent of season (restrictive vs. non-restrictive months) comparisons were made based on data (n compliant transits) averaged per month for 2015 and 2016 (using chi-square with Yates's correction for continuity).

Whales' distribution ranges were calculated from the filtered data using the kernel density estimator to generate surface values indicating higher or lower utilization of the space by the tracked whales. Kernel was calculated using the Spatial Analyst tool in ArcGis 10.2.2. Kernel density analyses were conducted for all individual whales regardless of sex. Kernel values were extracted from raster files for each transmission point [41].

3. Results

3.1. Whale density related to traffic separation schemes

The design of the three adopted TSS (Fig. 1a) reduced considerably the overlap area used by transiting vessels and humpback whales in Pacific Panama (Fig. 1b). Compared to previously occupied ca. 11,600 square kilometers of ship traffic across the Gulf of Panama in particular, the TSS area confined actual shipping traffic to an area of about 830 square kilometers (Fig. 1b). This change represented a reduction of 93% of the potential vessel-whale interaction area, similar to previous estimates [11].

3.2. Transmissions and ships

After cleaning the data a total of 41,999 individual (verified) transits between 2014 and 2016 (13,590 in 2014, 14,309 in 2015 and 14,100 in 2016, Table 1) were analyzed for the spatial analysis with minor deviations between individual months as well as inbound and outbound traffic (data not shown). To examine speed compliance, the filtered dataset comprised 13,106, 13,616 and 13,867 total transits for 2014, 2015 and 2016 respectively. Cargo vessels and tanker displayed the largest proportion over the study period, comprising between 68.1 and 80.2% and 17.2 and 27.8% between 2014 and 2016 respectively. The remaining vessel types (passenger, pilot, fishing and others) constituted less than 10% of total vessels observed (Table 1).

3.3. Compliance

3.3.1. TSS

Overall, there was a significant relationship between compliance rates and times before and after TSS implementation ($\chi^2 = 16828.34$, df = 2, P < 0.001); as predictable transits within TSS boundaries were 25.4% in 2014 and abruptly increased to 86.1% in 2015 and 89.8% in 2016 respectively (Table 2, Figs. 2 and 3). In addition, significant differences in compliance rates among vessel types were found (2015: $\chi^2 = 547.27$, df = 5, P < 0.001; 2016: $\chi^2 = 806.17$, df = 5, P < 0.001). Compliance was highest for cargo (88.5 and 87.6% in 2015 and 2016, respectively) and tanker vessels (92.1 and 88.0%), whilst the least compliant were fishing vessels (21.7 and 24.7%, Table 1). About 4.6 and 6.1% of total transits for 2015 and 2016 respectively had AIS data tracking points in the buffer zone and were considered as non-compliant. The transit rate in the buffer zone varied between 2.9 and 5.9% in 2015 and 3.5 and 10.7% in 2016, depending on the type of vessel, with fishing vessels accounting for the largest proportion.

3.3.2. Speed

Significant differences in compliance rates with speed limits could be observed among years ($\chi^2 = 497.86$, df = 2, P < 0.001). Yet, although speed compliance had increased since 2014, at that time including 4.6% compliant vessels, only a small proportion of mariners (19.0 and 9.7% in 2015 and 2016 respectively) adhered to the temporary 4-months 10 kn speed limit based on SOG (Table 2). Given water current velocities between 20 and 40 cm/s in the study area (see section 2.1), a difference of 10 ± 0.4 to 0.8 kn between SOG and STW was calculated. Assuming that ships were using STW against strong currents and 10.8 kn would therefore be the reference point, 46.9 and 46.6% of vessels corresponded to speed restrictions in 2015 and 2016, respectively. Comparison of ship compliance between restrictive and non-restrictive periods revealed a significant relationship ($\chi^2 = 5.138$, df = 1, P = 0.023), that is speed compliance was higher during restrictive months compared to non-restrictive months (Table 2). On average, ship speed decreased from non-restrictive periods (13.4 ± 3.0 and 13.5 ± 2.9 kn in 2015 and 2016) to times, where speed limits applied (11.2 ± 2.6 and 11.4 ± 2.6 kn, Table 3). In addition, average vessel speeds decreased slightly during the 4-months restrictive periods from 12.8 ± 3.1 kn in 2014 to 11.2 ± 2.6 kn and 11.4 ± 2.6 kn in 2015 and 2016 respectively (Table 3).

Analyses of speed compliance rates per vessel type were based on pooled data, as Chi-square tests require values of five or more. We detected a highly significant relationship between vessel class and the degree of compliance with speed limits ($\chi^2 = 51.712$, df = 5, P < 0.001). For all vessel types, the compliance rate increased from 2014 to 2015 and again dropped from 2015 to 2016. The largest initial effect following the implementation of speed limits was observed for cargo vessels, where speed compliance rate increased by 15.0% from 3.8% in 2014 to 18.8% in 2015 (factor 5.0), followed by tanker (times 3.3) and passenger (times 2.4) vessels (Fig. 4). However, overall compliance rates were lowest for cargo, tanker and passenger vessels, that is only between 15 and 18.8% in 2015 and 7.2 and 10.2% in 2016 of vessels adhered to temporary speed limits. By contrast, the highest (initial) compliance rates were found for pilot ships and "Others" at 66.7 and 57.1% in 2015 (Fig. 4). Remarkably, the compliance rates for the latter fell below pre-implementation levels in 2016 (32.0 and 45.5% for pilot ships or "others" in 2014 vs. 26.1 and 28.6% in 2016, Fig. 4). In a similar manner, the compliance rate for fishing vessels increased from 12.2% in

Table 2
Summary of compliance (%) with speed and TSS recommendations for all vessels crossing the Gulf of Panama between 2014 and 2016. Compliance TSS was calculated on the basis of total transits per year, whereas compliance Speed/TSS & Speed was calculated using total transits within a given period (restrictive vs. non-restrictive). %Compliance TSS or speed means that vessels were compliant with the TSS, but not necessarily the speed limit and vice versa. Data from 2014 is used as a control, as it includes pre-TSS AIS transmissions.

Year	Period	N transits	% Compliance TSS	% Compliance Speed	% Compliance TSS & Speed
2014	restrictive	(4644)	–	4.6	–
	non-restrictive	(8946)		4.2	–
2015	restrictive	4800	**86.1**	**19.0**	**18.2**
	non-restrictive	9509		3.6	3.2
2016	restrictive	4662	**89.8**	**9.7**	**9.2**
	non-restrictive	9438		3.3	2.8

Table 1
Differences in compliance (%) with the TSS between vessel types. In TSS: vessel remained within TSS boundaries at all times; Out TSS: vessels with at least one AIS data tracking point outside the TSS limit. Data from Dec 2013 to November 2014 (≙2014) are used as a control, as it includes pre-TSS AIS transmissions.

Vessel type	2014			2015			2016		
	In TSS	Out TSS	n total transits	In TSS	Out TSS	n total transits	In TSS	Out TSS	n total transits
Other	25.5	74.6	72	72.6	27.4	126	56.4	43.6	121
Fishing Vessel	15.7	84.3	100	21.6	78.4	197	24.7	75.3	153
Pilot Vessel	38.9	61.1	81	72.3	27.7	88	64.3	35.7	104
Passenger Vessel	16.2	83.8	150	68.3	31.8	173	68.2	31.8	133
Cargo Vessel	24.0	76.0	10,551	88.5	11.5	10,016	87.6	12.5	10,663
Tanker Vessel	31.9	68.1	2636	92.1	7.8	3500	88.0	12.0	3135

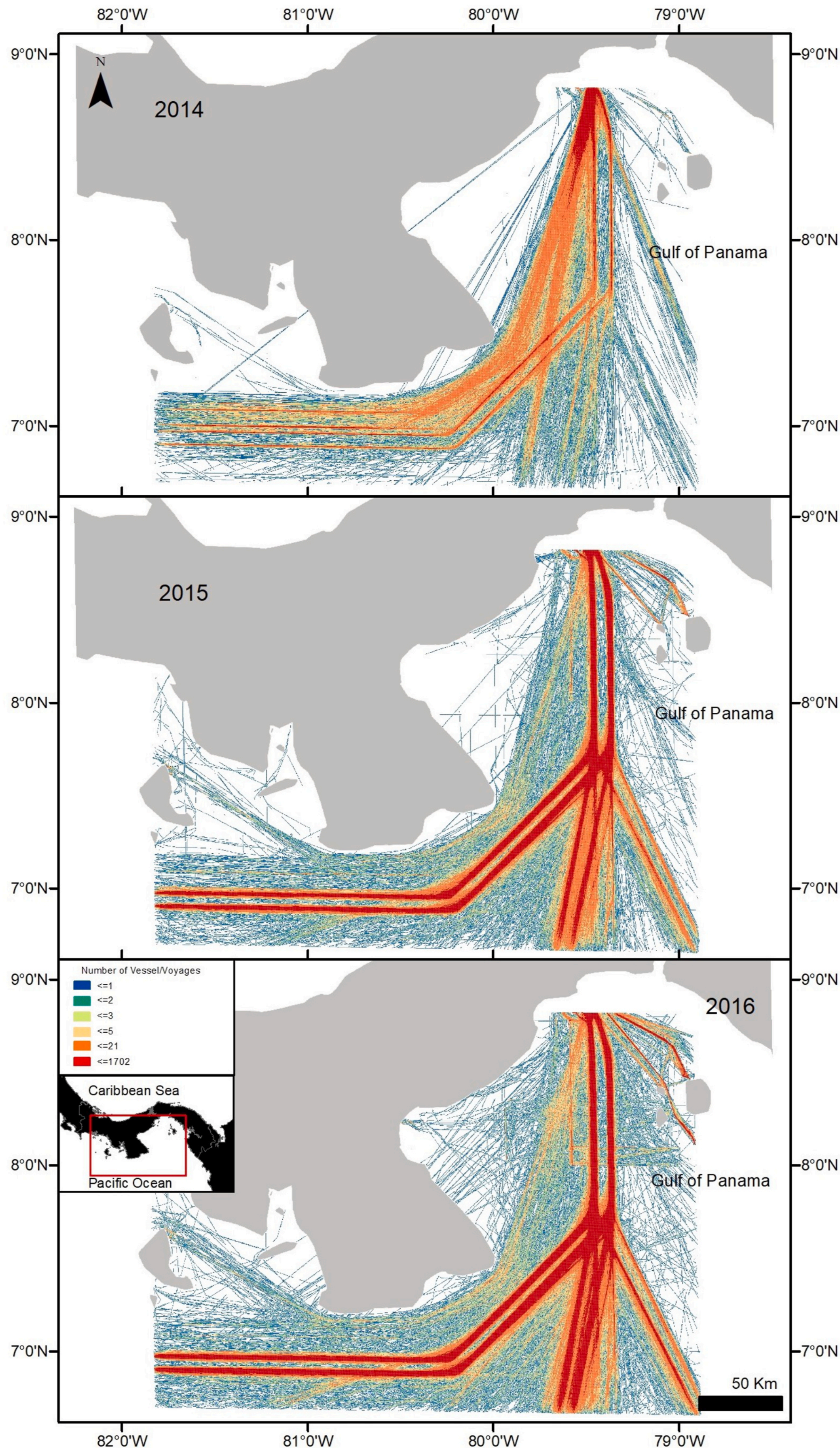

Fig. 2. Traffic density maps encompassing the network of three Traffic Separation Schemes adopted for Pacific Panama, for 2014 (top plot), 2015 (mid) and 2016 (bottom). Notice some vessel started using the TSS during 2014 few months before implementation.

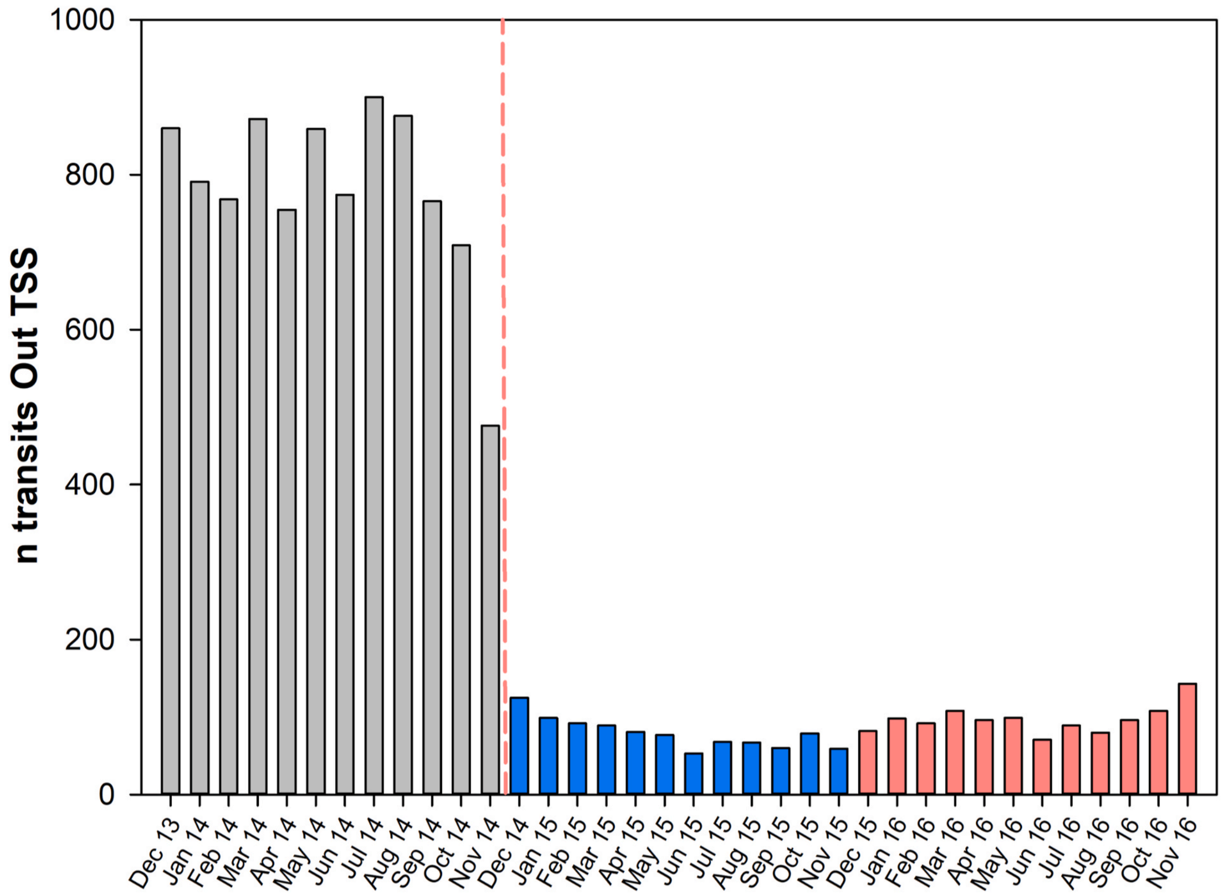

Fig. 3. Changes in vessel compliance following the implementation of the TSS in the Gulf of Panama per year and month. The graph illustrates the number of vessels outside TSS boundaries per month. The dashed line denotes the time of implementation of the TSS (Dec 1, 2014). Note: 2014 Dec 2013–Nov 2014; 2015 Dec 2014–Nov 2015; 2016 Dec 2015–Nov 2016. Data from Dec 2013 to November 2014 (≙2014) represent pre-TSS transits used as a control.

Table 3
Average vessel speed per vessel type and year during four-month restrictive (R) and eight-month non-restrictive (N) periods. Speed was compliant, when vessels traveled at ≤ 10 kn during the restrictive period (Aug–Nov); vessel speed in knots (mean ± SD).

Vessel type (AIStype#)	Year	N transits - total -	Average speed (N)	Average speed (R)	Non-compliant speed (N)	Non-compliant speed (R)	Non-compliant speed (R) - range -	Compliant speed (R)
Fishing (30)	2014	86	12.2 ± 1.6	11.1 ± 2.2	12.5 ± 1.1	12.0 ± 1.0	10.1–15.2	7.5 ± 1.9
	2015	113	11.7 ± 2.0	10.9 ± 2.1	12.2 ± 1.2	12.1 ± 1.5	10.1–15.7	8.8 ± 1.2
	2016	175	11.3 ± 2.1	11.5 ± 2.3	12.1 ± 1.2	12.4 ± 1.1	10.1–15.6	7.0 ± 2.7
Pilot (50–59)	2014	64	9.5 ± 2.2	10.15 ± 1.6	11.8 ± 1.4	11.4 ± 1.0	10.1–13.9	8.5 ± 0.9
	2015	79	9.9 ± 2.7	8.3 ± 2.3	12.1 ± 1.7	11.7 ± 1.1	10.1–14.2	7.0 ± 1.2
	2016	67	10.0 ± 2.6	9.5 ± 2.9	11.8 ± 1.6	11.5 ± 1.5	10.1–17.7	6.7 ± 2.4
Passenger (60–69)	2014	138	13.5 ± 3.3	14.1 ± 2.7	14.6 ± 2.3	14.3 ± 2.68	10.1–21.5	8.9 ± 1.4
	2015	116	13.5 ± 3.2	11.3 ± 2.9	14.4 ± 2.3	13.0 ± 2.6	10.1–20.5	8.1 ± 0.8
	2016	153	13.4 ± 3.0	11.5 ± 2.8	14.2 ± 2.3	12.7 ± 2.6	10.1–22.5	8.9 ± 0.6
Cargo (70–79)	2014	10,287	13.7 ± 3.2	13.1 ± 3.1	14.3 ± 2.7	13.8 ± 2.6	10.1–27.7	8.4 ± 1.6
	2015	10,308	13.7 ± 3.2	11.3 ± 2.7	14.2 ± 2.7	12.6 ± 2.4	10.1–28.9	8.9 ± 1.2
	2016	9953	13.8 ± 3.0	11.3 ± 2.5	14.3 ± 2.6	12.5 ± 2.4	10.1–29.9	8.9 ± 0.9
Tanker (80–89)	2014	2471	12.2 ± 2.5	11.9 ± 2.4	13.0 ± 1.5	12.7 ± 1.5	10.1–18.0	8.3 ± 1.3
	2015	2927	12.4 ± 2.3	11.2 ± 2.4	13.0 ± 1.4	12.5 ± 1.7	10.1–25.1	8.7 ± 1.4
	2016	3424	13.0 ± 2.0	11.4 ± 2.2	13.4 ± 1.5	12.4 ± 1.8	10.1–22.8	8.8 ± 1.1
Other (31–49)	2014	60	9.9 ± 3.4	7.2 ± 4.1	13.2 ± 2.2	13.2 ± 1.7	10.2–15.9	5.8 ± 2.3
	2015	73	11.7 ± 2.6	10.6 ± 2.0	12.5 ± 2.2	12.0 ± 1.6	10.2–15.3	8.8 ± 0.8
	2016	95	10.7 ± 3.3	13.0 ± 4.3	12.8 ± 2.0	115.0 ± 1.6	10.1–29.9	7.9 ± 1.3
Total	2014	13,106	13.4 ± 3.2	12.8 ± 3.1	14.1 ± 2.6	13.6 ± 2.5	10.1–27.7	8.0 ± 1.9
	2015	13,616	13.4 ± 3.0	11.2 ± 2.6	14.0 ± 2.6	12.5 ± 2.3	10.1–28.9	8.8 ± 1.2
	2016	13,867	13.5 ± 2.9	11.4 ± 2.6	14.0 ± 2.4	12.62 ± 2.28	10.10–29.90	8.85 ± 1.08

2014 to 26.1% in 2015 and then again dropped below pre-implementation levels, with only 6.7% of fishing vessels sailing at 10 kn or less in 2016 (Fig. 4). The average ship speed of pilot, passenger, cargo and tanker vessels decreased during the restrictive periods (2015/2016) compared to 2014, but remained, with the exception of pilot ships, at > 10 kn in all cases (Table 3). By contrast, average ship speed of vessels identified as "Others" increased markedly during restrictive periods, whilst it remained with a similar range for fishing vessels

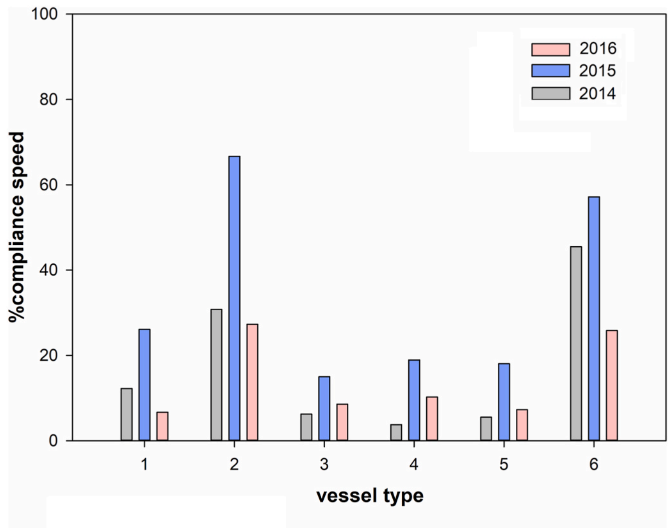

Fig. 4. Compliance (%) with temporary speed limits per vessel type. A ship is compliant when traveling at ≤10 kn during restrictive months (Aug–Nov). Data from Dec 2013 to November 2014 (≙2014) are used as a control, as it includes pre-TSS AIS transmissions.

(Table 3).

4. Discussion

The most effective ways to attenuate the risk of whale-vessel collisions include vessel routeing schemes, speed reductions or both [9,10,21,22]. While the first decreases the possibility of whale-vessel encounters [11], temporarily and/or spatially, lowering speed reduces the likelihood that the collision of whales and ships will be fatal [14,22]. Several studies could prove the successful implementation of such mitigation strategies. For instance, establishing the Ship Strike Rules in 2008, US and Canadian governments jointly adopted a number of regulations, including modified TSSs and speed reductions in the Bay of Fundy (NW Atlantic). As a result, the risk of lethal whale-vessel collisions could be reduced by 62% (TSS) and 52% (speed), while a combined solution (TSS and speed) would reduce the risk by as much as 75% [21,78]. Conn and Silber [22] found that seasonal speed restrictions (<10 kn) lowered the risk of lethal vessel strikes to the North Atlantic right whale (*Eubalaena glacialis*) along the US East coast by 80–90%. Furthermore, amendment of the Cabo de Gata (southern Spain) TSS in 2006 led to separation of vessels and cetaceans and hence reducing the risk of vessel strikes [10]. Though, efficacy of different management actions can only be achieved if operators comply with the proposed regulations and recommendations in the first place [10,23,25].

Our results revealed, that with the implementation of the Gulf of Panama TSS, most vessels instantly adhered to TSS boundaries (Fig. 3). There has also been a significant difference in speed compliance rates over the years. However, overall compliance was rather poor, i.e., only ~19% of vessels in 2015 and less than 10% in 2016 applied to recommended speed restrictions (Table 2), which can be considered too low for the mitigation from ship strikes and long-term protection of whales. A compliance level similar to that measured for the TSS could be considered adequate for speed restrictions.

Speed data provided by AIS indicate SOG, which is difficult to maintain for ships navigating in strong currents (57). Therefore, Chion et al. (57) recommended using Speed Through Water (STW) as an alternative measure. The water flow velocity in the Gulf of Panama varies between 20 and 40 cm/s [46,47], which leads to a discrepancy of 10 ± 0.4 to 0.8 kn between SOG and STW. But even if speeds were measured as STW and maximum current speeds were assumed, less than 50% of seafarers adhered to the speed limits. As the IMO does not clearly state whether the speed limit is related to SOG or STW [50], this can lead to confusion and seafarers may tend not to stick to the speed measurements.

The broad international acceptance of the IMO mandate means that IMO-adopted rules usually gain high compliance levels, be they recommendatory or mandatory [10,25,58,59]. TSSs are common tools implemented by the IMO to enhance safe maritime navigation, and compliance with TSS is mandatory according to Rule 10 of the IMO's International Regulations for Preventing Collisions at Sea (COLREGs) [51]. Speed reductions, by contrast, have rarely been adopted by the IMO for the purpose of whale protection, while considered a powerful tool to reduce collision with large whales [22,60]. In fact, there is currently only one other IMO-approved speed limit for the Strait of Gibraltar TSS, where vessel compliance with a recommended maximum speed of 13 kn was also low [10]. Silber et al. [10] suggested that, unlike TSS, speed limits might not have been accepted yet as a mitigation strategy. The seasonality of speed limits, as opposed to a permanent restriction in case of the TSS, may furthermore result in the operators being insufficiently informed and unfamiliar with this conservation measure [64]. In addition, there seems to be a difference in whether new measures are endorsed or merely being noted by the IMO [10,61]. In the case of the Gulf of Panama TSS, the IMO endorsed a temporary speed limit for ships transiting the TSS, but only as a recommendation [50], which has been clearly not accepted yet.

Generally, there is a tendency that operators more likely adhere to mandatory rather than recommendatory measures [23,62], but see Ref. [57]. Furthermore, there seems to be a greater acceptance to follow routeing schemes than imposed speed restrictions [21,63]. This could be due to several factors, including perception and acceptance of new measures, and whether the benefits of compliant behavior outbalance its consequences [23,63,64]; that is what would be the actual risk and impact of a whale-vessel strike (for ship and crew), how much would ship operations be affected by compliance and what are the associated costs [64]? Vessels tend to adhere to routeing schemes, also voluntary ones, as they are easy to implement and make ship movements more predictable, thereby reducing the risk of collisions [21,63,65]. Speed limits, on the other hand, can considerably increase at-sea times and therefore costs [21,62,63]. Gonjo et al. [66] estimated that re-routeing of vessels off the Channel Islands (southern California) would reduce shipping costs by 1.6%–3.4%, while speed limits would increase costs by 1.3%–2.0%. However, shipping companies can anticipate speed restrictions and compensate for any loss of time by increasing speed in non-restricted areas along the route.

For the Gulf of Panama, speed reductions apply for a total length of approximately 83 km (44.8 nmi) of the 110.9 km TSS and starting at 8°N to the north [50]. Prior to the implementation of the Gulf of Panama TSS, highest average speeds were observed for cargo, tanker and passenger vessels, which, as elsewhere, also accounted for the largest proportion of vessels (Tables 1 and 3) [67]. In 2014, the non-compliant speed during restrictive periods was on average 14.39 ± 2.7, 13.0 ± 1.5 and 14.6 ± 2.3 kn for cargo, tanker and passenger vessels respectively (Table 3). Thus, reducing the ship speed to 10 kn for these vessel classes would have increased transit times from an average of 3.1–3.5 h to ≥4.5 h. A speed limit would therefore have the greatest impact on the operation of these vessels [23], but also vice versa; that is, due to their size and high average speeds, cargo, tank and passenger vessels also present an increased threat for whales [9,11].

The two approximately 37,815 km^2 ITZ adopted and mandatory for Pacific Panama added supplementary protection to coastal habitats used by the whales (Fig. 1b) reducing potential collisions, while functioning as ATBAs [*sensu* [21]. Fishing vessels, in particular tuna fishing vessels, were the ship class with most TSS violations while in clear transit to ports (the inshore traffic zones adopted by IMO and local regulations do not allow tuna fishing inside the gulf area), and these also showed very low compliance with speed limits (Fig. 4, Table 1). This lack of compliance by tuna fishing vessels coupled with average non-compliant speeds of 12.0 ± 1.0 (2014), 12.1 ± 1.5 (2015) and 12.4 ± 1.1 kn (2016) during restrictive periods represent a major threat to humpback whales in the Gulf of Panama. It is not clear though, whether the ships within the 0.2 nmi buffer zone were definitely outside the TSS limits or whether this was due to inaccurate tracking of the ship's positions, resulting in a slight overestimation of non-compliance. However, even if ships in the buffer zone (and inside the ITZ) are classified as TSS compliant, this does not alter the overall results and fishing vessels remain the least responsive to spatial measurements.

Generally, fishing vessels fall under the requirements of COLREG's Rule 10 (d); that is all ships are requested to use the TSS as long as safe transit is ensured, except for vessels of <20 m, sailing vessels and those engaged in fishing, which may use inshore traffic zones (ITZ) [51]. This rule, and associated use of the ITZ, was established to segregate large fast ships from small industrial and artisanal fisheries. However, tuna vessels observed in our study, that typically exceed 20 m and >100 gross tons, were in transit to ports at high speed and not engaged in fishing. Therefore, the Panama Maritime Authority, as the regulatory organ to ensure compliance with the TSS in Panama, can request the use of the mandatory TSS for tuna fishing vessels during transit and report any infringements to the IMO.

Unfortunately, the updated government data to assess the effects of TSS implementation and speed on vessel-related injuries and lethality of humpback whales in Pacific Panama can only be incidental due to the limited time-series information available. Between 2017 and 2019 (36 months) eight large whales were reported dead: three Bryde whales (*Balaenoptera brydei*), five humpbacks and one unknown, with no autopsies reported. In contrast, Guzman et al. [11] reported 13 death whales in 29 months between 2009 and 2011, mostly humpbacks. This is a slightly reduction in whale mortality in a comparable timeframe. Although it is anticipated that the Gulf of Panama TSS will have considerably decreased spatial co-occurrence of whales and vessels [11], achieving compliance to speed limits has not been very successful despite its importance in alleviating the risk of fatal vessel strikes [*sensu* [9,15,22,44,60,25,68]. In humpback whales, the average speed for (non-singing) whales during migration is about 4.0 km/h, with the velocity being significantly lower for mother-calf groups and singing individuals [69]. Thus, lowering the speed not only increases the whale's response time and helps to avoid collisions, but also allows the vessel to be stopped and/or maneuvered [70].

Compliance with conservation requirements is usually enhanced through knowledge sharing, collaborative planning processes between conservation agencies and shipping industries, as well as the enforcement of conservation measures [15,30,71]. Chion et al. [57] could demonstrate that a co-construction (bottom-up) approach between members of the maritime/industry authorities, governmental and non-governmental organizations, and scientists greatly enhanced commitment to voluntary speed limitations in the St. Lawrence Estuary (Quebec, Canada). Thus, engaging the Panamanian maritime sector and conservation authorities in concerted efforts to ensure safe and cost-effective shipping and concomitantly achieve conservation goals can contribute to better compliance [*sensu* [10,64,71]. This may involve education and outreach programs to inform mariners about speed limits and their crucial role for reducing whale-vessel collisions, but also consideration of operational requirements and constraints of marine industries during the implementation phase [10,72]. In addition, marine mammal observation (MMO) programs and near real-time information on whale sightings (e.g., via AIS, NAVTEX, VHF) can provide complementary tools to help mariners to actively avoid whales [10,64,73,74]. If feasible, enforcement actions should be considered, including fines and reporting of violations, as these have been demonstrated to considerably improve compliant behavior [23], but are also quite expensive requiring staff, training and equipment [23,30,75]. As a first step, speed will need to become mandatory and enforced by the flag and/or port state [59, 76]. Above all though, we strongly encourage the Panama Maritime Authority to approach IMO members with a revised normative to make speed limits mandatory for the Gulf of Panama. Alternatively, Panama can unilaterally consider a mandatory speed restriction based on a recent legislation (Law No. 47 of August 28, 2018), which modified the limits for territorial waters and extended the baseline further south, near latitude 07°N, encompassing the entire Gulf of Panama under the nation's internal jurisdictional waters.

5. Conclusions

Our results indicated that the new IMO measures to mitigate the risk of ship collisions with migratory humpback whales in the Gulf of Panama evoked different compliance responses. Although mandatory TSS compliance can be considered promising, alternative measures, including non-voluntary and mandatory options, should be sought to manage speed restrictions. In addition, the use of the ITZs by tuna fishing vessels in transit to/from Panamanian ports needs to be reconsidered to warrant further protection to whales.

Future studies will need to be conducted to monitor and re-assess compliance, also because the implementation of speed limits may take several years [*sensu* [23]. In addition, continuous monitoring is required to detect any injury and mortality of whales associated with ship strikes and thus assessing the effectiveness of conservation measures. Nevertheless, we recognize the difficulties to obtain reliable strike data owing to the unnoticed nature of the accidents during navigation. The expected increase in maritime traffic, also due to the expansion of the Panama Canal, will unequivocally increase the vessel-strike risk to whales [11, 22,77]. During the humpbacks high season, it is finally recommended to increase port reminders for vessels arriving or departing from the Pacific anchorage area via the Port Entry Coordinator (PEC) in the Flamenco signal station on VHF's Channel 12 in order to prevent/reduce the collisions of whales and vessels transiting the Gulf of Panama TSS. Overall, and with the joint efforts of the Panama Canal Authority, PMA and the Panama Maritime Chamber, communication with mariners needs to be enhanced.

Declaration of competing interest

The authors declare no conflict of interest with local authorities or data providers.

CRediT authorship contribution statement

Hector M. Guzman: Conceptualization, Methodology, Investigation, Data curation, Writing - review & editing, Supervision, Funding acquisition. **Natasha Hinojosa:** Data curation. **Stefanie Kaiser:** Investigation, Formal analysis, Writing - original draft, Writing - review & editing.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpol.2020.104113.

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