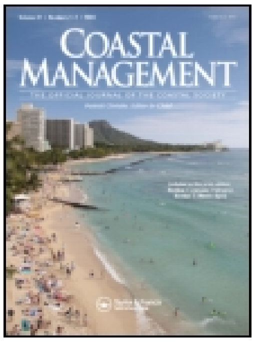

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Spatial and Temporal Variability in Shipping Traffic Off San Francisco, California

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Shipping traffic poses a worldwide threat to many large whale species. Spatially explicit risk assessments are increasingly being used as a tool to minimize ship-strike risk. These assessments often use static representations of shipping patterns. We used Automatic Identification System data to quantify variability in cargo shipping traffic entering and exiting San Francisco Bay, which contains some of the busiest ports in the United States, at three temporal resolutions: (1) before and after implementation of the California Air Resources Board's Ocean-Going Vessels Fuel Rule, (2) among seasons, and (3) day versus night. We used the nonparametric Mood's Median test to compare median daily distance traveled because the data were not normally distributed and the variance was not homogeneous. Our analyses show that shipping traffic off San Francisco is dynamic at both interannual and daily temporal resolutions, but that traffic was fairly consistent among the seasons considered. Our analyses emphasize the importance of economic and regulatory drivers on interannual shipping traffic patterns. Shipping traffic is expected to continue to change off the U.S. West Coast and to increase globally. These changes in shipping traffic could have implications for the risk of ships striking whales and should be included in risk assessments.

Keywords Automatic Identification System (AIS), cargo ships, geographic information system (GIS), San Francisco Bay, ship strike

Introduction

Shipping traffic poses a worldwide threat to many large whale species (Laist et al. 2001) because collisions between ships and whales can lead to increased mortality and jeopardize the viability of small populations (Fujiwara and Caswell 2001). Spatially explicit risk assessments are increasingly being used as a tool to minimize risk associated with anthropogenic activities in the marine environment (Stelzenmüller, Ellis, and Rogers 2010; Grech, Coles, and Marsh 2011). Ship-strike risk assessments require two

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components: whale distribution maps and ship traffic maps (e.g., Redfern et al. 2013). Several assessments of ship-strike risk use static maps of shipping traffic (e.g., using a single year of traffic data) (Vanderlaan et al. 2008; Wiley et al. 2011; Williams and O'Hara 2010). However, there are several drivers of change in maritime transportation (Rodrigue 2010b). Environmental drivers, such as the changing sea ice extent caused by climate change, will impact navigation around the globe (Smith and Stephenson 2013). Social drivers, such as the economy and policy, also influence shipping (McKenna et al. 2012a). It is increasingly important to understand these drivers and their effects on shipping because maritime traffic, especially commercial shipping, continues to grow worldwide (Frisk 2012; McDonald, Hildebrand, and Wiggins 2006).

On the U.S. west coast, both economic and regulatory drivers have been observed to affect shipping patterns. For example, McKenna et al. (2012a) found that the global economic recession of 2007–09 caused a reduction in shipping traffic. They also found that implementation of the California Air Resources Board's Ocean-Going Vessels Fuel Rule (hereafter, CARB rule) caused shifts in traffic patterns (McKenna et al. 2012a). The CARB rule aims to improve air quality and public health in California by reducing the amount of particulate matter, oxides of nitrogen, and sulfur oxide added to the atmosphere from vessel fuel emissions and has been implemented in two phases (CARB 2013). The first phase, which began on July 1, 2009, required vessels traveling within 24 nmi of the contiguous California Coast to use marine diesel oil containing less than or equal to 0.5% sulfur (CCR 2009). A second phase of the rule began on January 1, 2014 and requires vessels traveling within this same area to use fuels that have less than or equal to 0.1% sulfur content.

Low-sulfur fuels are more expensive than traditional high-sulfur bunker fuels (Dupin 2013) and their lower viscosity and lubricity levels can lead to a variety of mechanical and safety issues for mariners (UK P&I Club 2012). It is therefore perceived to be advantageous by vessel operators to use cheaper, high-sulfur fuels when possible. In the Southern California Bight, mariners shifted their routes from the Santa Barbara Channel to areas south of the northern Channel Islands after the first phase of the CARB rule was implemented to reduce the time spent using low-sulfur fuels (McKenna et al. 2012a). Redfern et al. (2013) incorporated this shift in traffic in a ship-strike risk assessment for Southern California and found changes in risk for fin and humpback whales after implementation of the CARB rule.

We analyzed cargo ship traffic off San Francisco, a site of extensive shipping activity (Watkins 2007). Most vessels transiting this area are destined for the Ports of Oakland and Richmond, which are located within San Francisco Bay (SFB) and are some of the busiest ports in the United States (USACE 2013a). In 2012, the Port of Oakland had the sixth largest volume of cargo containers in the United States (USACE 2013b) and the 53rd largest in the world (AAPA 2013). The SFB is accessed through a traffic separation scheme (TSS) established by the International Maritime Organization (IMO) in 1973 (USCG 2013). The TSS consists of a Precautionary Area, a Northern Approach, a Southern Approach, and a Western Approach (Figure 1). Each of these approaches includes both an inbound and outbound lane. Ships using the TSS are likely to travel through the Cordell Bank, Gulf of the Farallones, or Monterey Bay National Marine Sanctuaries (NMS). At the time of writing, these three Sanctuaries covered 5,972 square nmi off the coast of Central California (ONMS 2010). In 2015, Cordell Bank NMS will expand by 757 square nmi and Gulf of the Farallones NMS by 2013 square nmi (CFR 2015). These Sanctuaries protect important habitat for three species of whales: blue (*Balaenoptera musculus*) (Calambokidis et al. 2015; Irvine et al. 2014), humpback (*Megaptera novaeangliae*) (Yen, Sydeman, and Hyrenbach 2004; Keiper et al. 2005; Dransfield et al. 2014),

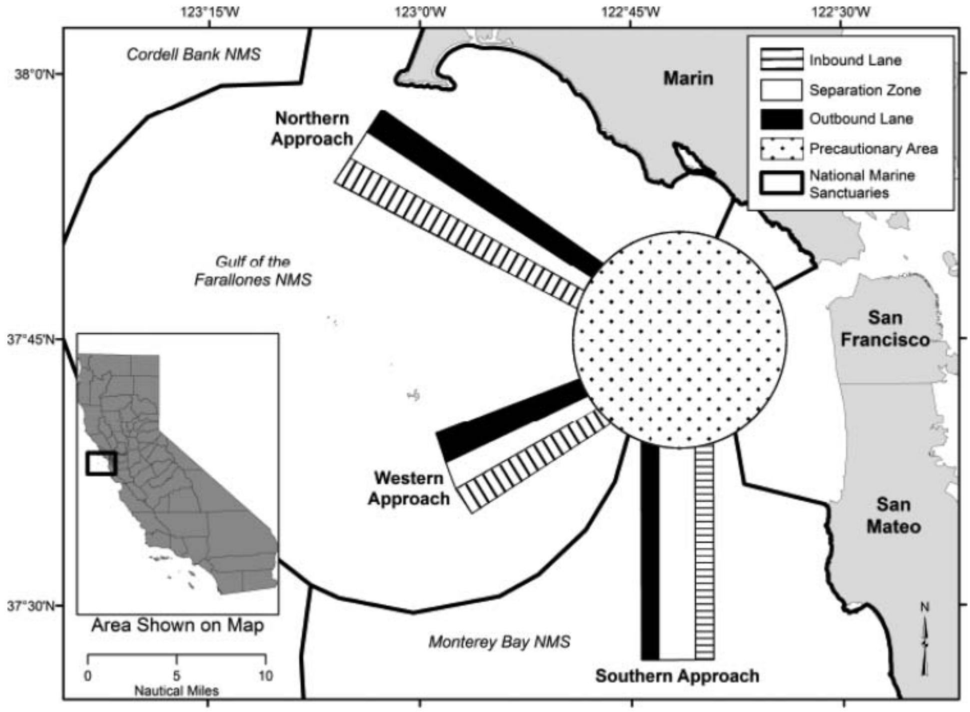

Figure 1. Study area. Map of the study region, including the Traffic Separation Scheme (TSS) and National Marine Sanctuaries (NMS) off San Francisco. The TSS consists of a Precautionary Area, a Northern Approach, a Southern Approach, and a Western Approach. Each of these approaches includes both an inbound and outbound lane leading into or out of San Francisco Bay, respectively. This map shows the TSS that was in effect during the study period (2009–2011).

and gray whales (*Eschrichtius robustus*) (ONMS 2010). Blue and humpback whales are listed as endangered under the U.S. Endangered Species Act. While blue and humpback whales forage along the continental shelf in the Sanctuaries from July to November (Calambokidis et al. 2015; Irvine et al. 2014), gray whales use coastal areas from October to early January and from mid-February to May during their annual migration (Perrin, Wursig, and Thewissen 2002).

The National Oceanic and Atmospheric Administration's (NOAA) National Marine Fisheries Service (NMFS) has identified ship strikes as a threat to blue and humpback whales in the Eastern Pacific (NMFS 1991, 1998). The large proportion of cargo ships traveling into SFB (76% of the distance traveled by both cargo ships and tankers in the TSS between 2009–11, Jensen 2014) raises concern because Laist et al. (2001) found that large vessels (i.e., ships 80 m or longer) were responsible for most of the whale–ship collisions that resulted in whale mortality or severe injury. For example, at least four blue whales are confirmed to have been killed by ship strikes off Southern California in 2007 (Berman-Kowalewski et al. 2010). There were 15 documented ship strikes of blue, humpback, and gray whales off San Francisco between 2005 and 2014 (NMFS West Coast Region 2015 pers. comm.). The true number of strikes is likely much higher because ship strikes have a low probability of detection (Laist et al. 2001).

We quantified variability in cargo shipping traffic off SFB at multiple temporal resolutions in 2009–11 using Automatic Identification System (AIS) data, which will help to identify the temporal resolutions needed for ship-strike risk assessments. First, we estimated cargo traffic both before and after implementation of the first phase of the CARB rule. Second, we compared seasonal variability in cargo traffic because different species have been shown to use different parts of the study area at different times of the year (Calambokidis et al. 2015; Perrin, Wursig, and Thewissen 2002; Irvine et al. 2014). Lastly, we compared daytime and nighttime traffic patterns of cargo ships to complement research showing that blue whales spend more time at the surface at night (Calambokidis et al. 2007).

Materials and Methods

Data Collection

We used AIS data to examine cargo traffic outside SFB in 2009, 2010, and 2011. AIS is a maritime tracking system adopted by the IMO and is required on international voyages for all vessels over 300 gross tons, although requirements are continuously evolving (IMO 2014; CFR 2003). AIS data provide information such as vessel speed, type, heading, and geographic position (Tetreault 2005). Examples of applications of AIS data include the examination of shipping patterns (McKenna et al. 2012a), monitoring responses to requests for voluntary speed reductions (McKenna et al. 2012b), whale–ship co-occurrence (Redfern et al. 2013), and the relationship between ship speed and the probability of a whale being killed upon collision (Wiley et al. 2011). The Cordell Bank and Gulf of the Farallones NMS Joint Working Group on Vessel Strikes and Acoustic Impacts also used AIS data to recommend modifications to the shipping lanes to reduce co-occurrence of shipping traffic and important whale habitat (JWG 2012). The proposal was approved by the IMO and implemented on June 1, 2013 (CFR 2013).

We accessed and downloaded monthly AIS data (UTM Zone 10) covering the San Francisco TSS for the years 2009, 2010, and 2011 from the NOAA Coastal Services Center's Marine Cadastre website (www.marinecadastre.gov). Data were provided in an ESRI file geodatabase format (ESRI 2014), allowing for exploration and analysis with a geographic information system (GIS). Each file geodatabase contained two different types of data. First, position reports provided dynamic vessel data at 1-minute intervals, including geospatial location, time, heading, navigational status, and Maritime Mobile Service Identity (MMSI). Navigational status indicates whether a ship is underway or at anchor. The MMSI is a nine-digit number used in AIS data to uniquely identify a vessel (USCG 2014). Second, voyage data provided information about a particular vessel and its voyage, including vessel name, dimensions, type, destination, estimated time of arrival, voyage ID, and MMSI. All vessel data were projected using an equal area projection.

We analyzed AIS data collected from 2009–11 because data for years preceding 2009 were not complete and data for years following 2011 were not available. We omitted the month of June from all analyses because the data from June 5–30, 2009 were missing. We selected data for cargo ships that had valid MMSI values (between 201000000 and 775999999), speed over ground > 0, and a navigational status of under-way using engine, restricted maneuverability, under-way sailing, or undefined (i.e., we did not analyze data for ships with invalid identifiers or that were at anchor). Data were assigned to seasons and day/night using Pacific Standard Time (PST). We defined seasons based on calendar quarters, with winter assigned to January–March, spring assigned to April–May (i.e., June is omitted from all analyses), summer assigned to July–September, and autumn assigned to October–December. These definitions largely coincide with those used by other studies of cetaceans in the California Current ecosystem (Forney and Barlow 1998;

Becker et al. 2014). We defined day and night using published nautical twilight times in Pacific Standard Time for 2009. Values from 2009 were used for all data because nautical twilight times do not vary appreciably across years (USNO 2013).

We generated vessel transit lines from the points in the vessel position reports. Specifically, points were joined in chronological order to form a line if both points had the same MMSI and voyage ID numbers and the elapsed time between points was less than one hour. If the elapsed time was greater than one hour and less than 24 hours, points that had less than a 30° change in heading were joined. If two successive points failed to meet these criteria, the script ended the current line and started another.

Analysis

We used a GIS to overlay the shipping lanes with the vessel transit lines and calculated the distance traveled within each lane. Specifically, we calculated the daily distance traveled by cargo ships at three temporal resolutions: (1) before and after implementation of the first phase of the CARB rule; (2) seasonally; and (3) day versus night.

We found that the daily distances were not normally distributed using the Shapiro-Wilk test. The distributions were positively skewed due to the presence of multiple zeros (indicative of days with no travel). We found that variance in daily distance traveled was not homogeneous using a nonparametric version of Levene's test. Consequently, we used the nonparametric Mood's Median test to compare distance traveled in each lane at the different temporal resolutions (we defined significance as $p < .05$) because it does not assume normality or homogeneity of variance. The data satisfy the assumption of independence because the spatial location of one vessel does not influence the location of other vessels at the scale of a traffic lane (i.e., each vessel selects their traffic lane independently, Berge 2014, personal communication). While not as robust as other statistical tests, the conservative nature of the Median test ensures fewer type I errors (Mood, Graybill, and Boes 1974, 521–522).

We used AIS data from 2009–11 to compare cargo ship traffic before and after implementation of the CARB rule on July 1, 2009 (hereafter, Pre- and Post-CARB). Our Pre-CARB data consisted only of January–May in 2009; consequently, we used data from these months in the two Post-CARB periods (i.e., 2010–11) in all comparisons to maintain consistency within the data.

We did not use the 2009 data for the seasonal and day vs. night analyses to eliminate any potential influence of the CARB rule. We compared median daily distances to determine variability among seasons in both 2010 and 2011. Post-hoc comparisons between pairs of seasons were performed for lanes found to have significant differences among seasons within a year. We also compared median daily distances traveled during the day and night in both 2010 and 2011.

Results

Detailed results from Mood's Median test are reported in the supplemental material for each temporal resolution.

Pre- versus Post-CARB

In 2010, after the CARB rule was implemented, traffic in the Northern Outbound and Southern Inbound lanes significantly decreased to 30.02 nmi/day (a 34.2% decrease) and

Table 1
Median daily distance traveled (nmi/day) in each CARB period

	Pre-CARB	Post-CARB$_{2010}$	Post-CARB$_{2011}$
North_In	15.31	15.33	15.38
North_Out	45.59	30.02	30.42
South_In	46.97	12.21	12.12
South_Out	12.18	0	0
West_In	0	28.87	42.48
West_Out	8.81	27.1	35.44

Note that data comparisons across the different TSS approaches (Northern vs. Southern vs. Western) should be avoided as the lane lengths are different (N ~ 15.1 nmi, S ~ 12.2 nmi, W ~ 8.8 nmi).

12.21 nmi/day (a 74% decrease), respectively (Table 1 and Figure 2). In contrast, traffic in the Western lanes significantly increased. Specifically, the Western Inbound lane increased from a median daily distance of 0 nmi/day (Pre-CARB) to 28.87 nmi/day (Post-CARB$_{2010}$), and the Western Outbound lane more than tripled its median daily distance from 8.81 nmi/day (Pre-CARB) to 27.10 nmi/day (Post-CARB$_{2010}$).

Median daily distances did not vary significantly between the two Post-CARB periods for three out of the six lanes. Both the Western Inbound and Western Outbound lanes showed increases in traffic between 2010 and 2011, while the Southern Inbound lane showed a decrease in traffic.

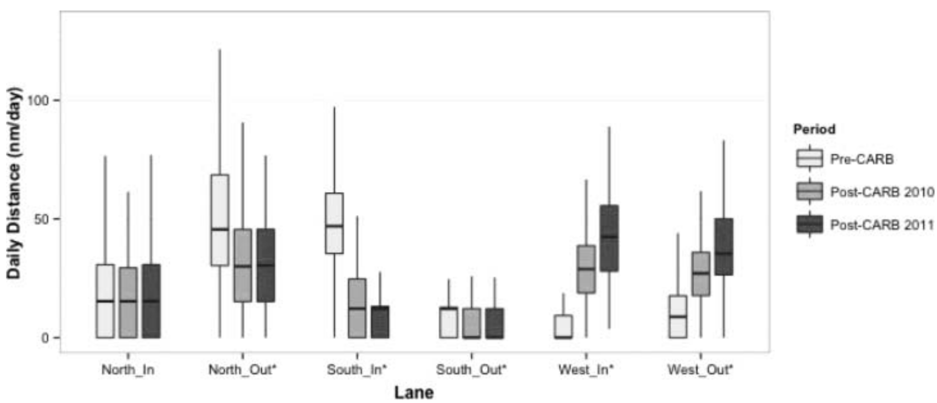

Figure 2. Daily distance traveled before and after CARB rule. Box and whisker plots show daily distance traveled by cargo ships before and after implementation of the CARB fuel rule. The bottom of the box symbolizes the first quartile, the middle line is the median, and the top of the box is the third quartile. The whiskers extending from the top and bottom of the boxes represent the range. Outliers are not shown. Significance is denoted by * ($p < .05$). Sample sizes were $n_1 = 151$ days (Pre-CARB), $n_2 = 151$ days (Post-CARB 2010), and $n_3 = 151$ days (Post-CARB 2011). Note that data comparisons across the different TSS approaches (Northern vs. Southern vs. Western) should be avoided as the lane lengths are different (N ~ 15.1 nmi, S ~ 12.2 nmi, W ~ 8.8 nmi).

Seasons

First and third quartiles and median daily distance traveled in 2010 and 2011 are reported in the supplemental material for winter ($n_1 = 90$ days), spring ($n_2 = 61$ days), summer ($n_3 = 92$ days), and autumn ($n_4 = 92$ days). We found that the median daily distance was significantly different among the 2010 seasons in three of the six shipping lanes: Southern Inbound, Western Inbound, and Western Outbound (Table 2). For the Southern Inbound lane, spring had a significantly higher median daily distance than the other seasons (Figure 3a). For both the Western Inbound and Outbound lanes, traffic appeared to increase throughout 2010, with the highest median daily distance traveled in autumn. No significant differences were observed among seasons in 2011 (Figure 3b).

Day versus Night

First and third quartiles and median daily distance traveled during the day and at night in each lane during 2010 and 2011 ($n = 335$ days) are reported in the Supplemental Material. Nine of these 12 comparisons showed significantly more traffic during the day than at night (Table 3 and Figure 4a–b). Higher traffic at night was only observed in the Western Inbound lane during 2011 (18.74 nmi/day during the day and 19.21 nmi/day at night).

Discussion

McKenna et al. (2012a) found that vessel operators in southern California shifted their routes to reduce time spent using more expensive low-sulfur fuels following implementation of the first phase of the CARB rule. Results from our analysis of shipping traffic off San Francisco before and after implementation of the first phase of the CARB rule showed similar shifts. Specifically, mariners reduced use of the alongshore lanes (Northern Outbound and Southern Inbound) and increased use of the offshore lanes (Western Inbound and Outbound) after the CARB rule was implemented (Figure 5).

Although seasonal differences were detected for three lanes during 2010, these differences can primarily be attributed to longer-term economic changes. Specifically, the seasonal differences in both Western lanes resulted from the increasing traffic observed

Table 2
Median daily distance traveled (nmi/day) in each season

	2010				2011			
	WTR	*SPR*	*SUM*	*AUT*	*WTR*	*SPR*	*SUM*	*AUT*
North_In	15.32	15.34	15.44	15.4	15.36	15.57	16.33	16.14
North_Out	30.19	24.21	30.42	15.84	30.36	30.47	30.73	30.43
South_In	12.16	12.44	12.19	12.21	8.44	12.16	12.12	0
South_Out	0	0	0	0	0	0	0	0
West_In	28.72	31.27	36.86	39.17	44.56	39.53	42.94	37.12
West_Out	27.07	27.67	35.21	35.88	35.6	35.38	35.94	35.06

Note that data comparisons across the different TSS approaches (Northern vs. Southern vs. Western) should be avoided as the lane lengths are different (N $\sim$ 15.1 nmi, S $\sim$ 12.2 nmi, W $\sim$ 8.8 nmi).

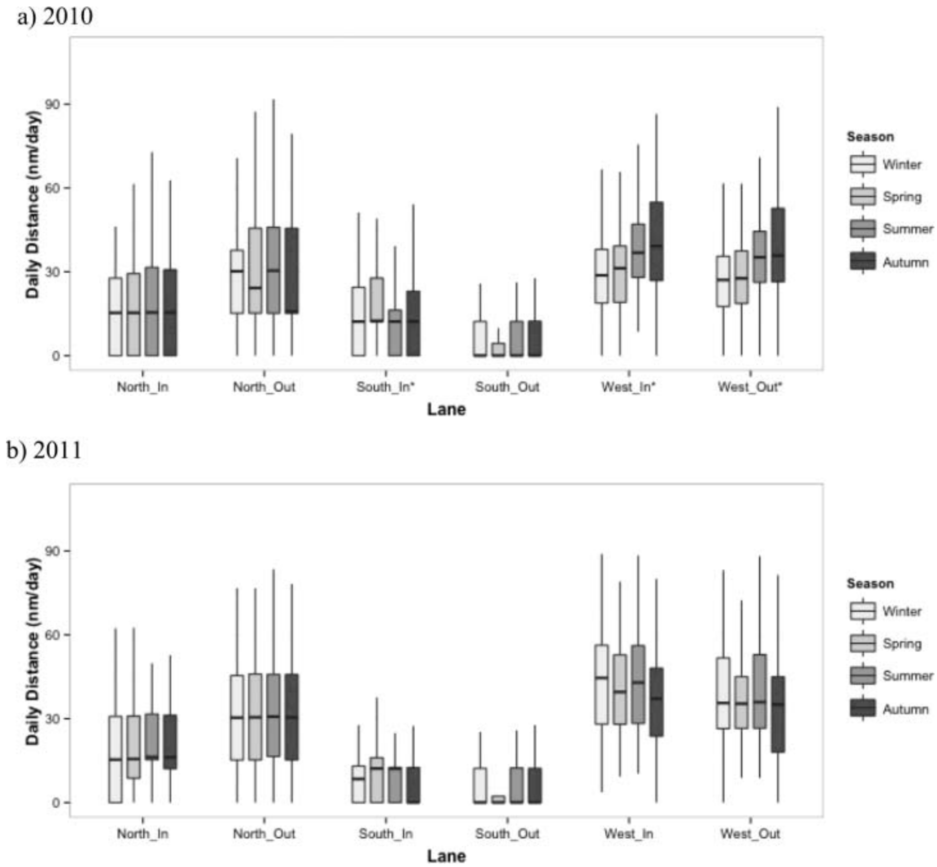

Figure 3. Daily distance traveled within each season. Box and whisker plots show daily distance traveled by cargo ships within each season in (a) 2010 and (b) 2011. Outliers are not shown. Sample sizes were $n_1 = 90$ days (winter), $n_2 = 61$ days (spring), $n_3 = 92$ days (summer), and $n_4 = 92$ days (autumn).

throughout 2010. This increase in traffic may have been caused by a partial economic recovery in the container shipping industry (cargo ships are part of this industry) after the 2009 recession (MKC 2012). While the Port of Oakland saw an overall 8.4% decrease in container ship imports and exports in 2009, there was a 13.9% increase in 2010 followed by a 0.5% increase in 2011 (Port of Oakland 2014). Although both the distance traveled by cargo ships and container ship imports increased in 2010 in our study area, there may not be a direct relationship between these increases in other regions. Specifically, if ship sizes increase, imports could increase without a concomitant increase in shipping traffic.

Results from our day versus night analyses indicate that there is a significant difference between day and night travel, with generally more distance traveled during the day. There was one exception in the Western Inbound lane in 2011, where more distance was traveled at night. While it appears that cargo ships generally travel more during the day, local resource managers should be aware of nighttime traffic in the Western Inbound lane as a potential increased risk for blue whales, which spend more time at the ocean surface at night (Calambokidis et al. 2007). There could also be an increased risk for humpback and gray whales, but less is known about the behaviors of these species at night.

Table 3
Median daily distance traveled (nmi/day) for day versus night

	2010		2011	
	Day	Night	Day	Night
North_In	4.89	0	15.31	0
North_Out	15.2	9.16	15.25	14.26
South_In	0	0	0	0
South_Out	0	0	0	0
West_In	18.59	15.17	18.74	19.21
West_Out	17.71	10.14	19.06	10.01

Note that data comparisons across the different TSS approaches (Northern vs. Southern vs. Western) should be avoided as the lane lengths are different (N ∼ 15.1 nmi, S ∼ 12.2 nmi, W ∼ 8.8 nmi).

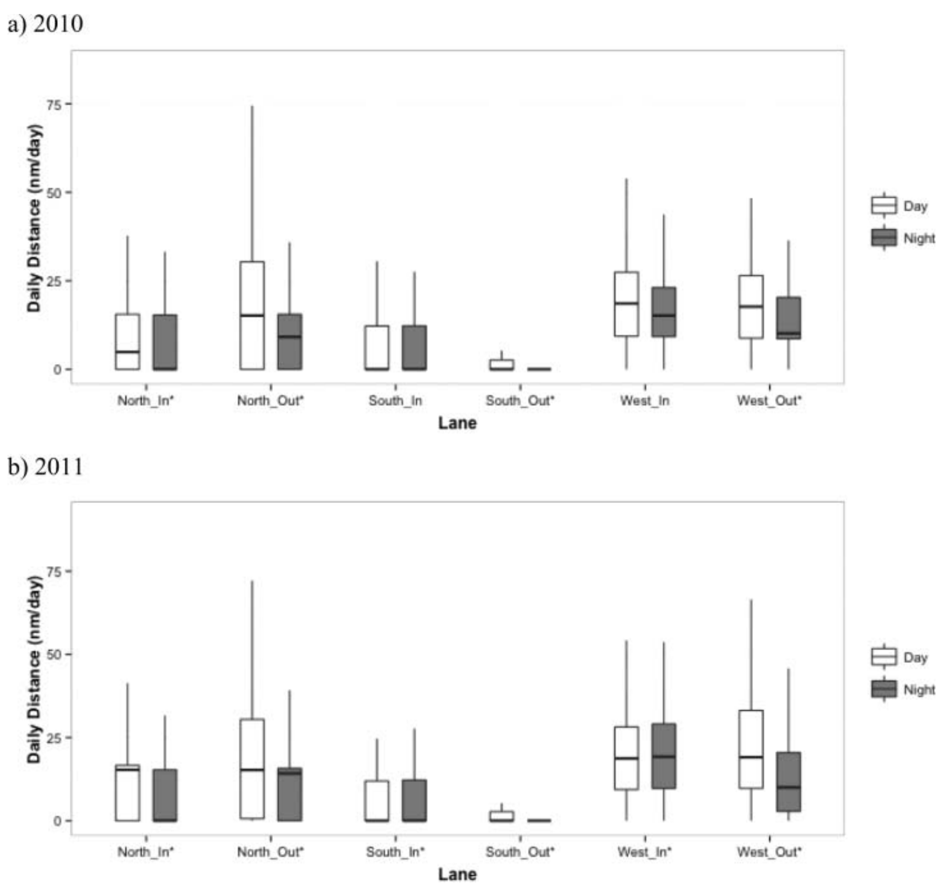

Figure 4. Daily distance traveled during the day versus at night. Box and whisker plots show daily distance traveled by cargo ships during day and night in (a) 2010 and (b) 2011. Outliers are not shown. Sample sizes were the same for both day and night travel: $n_1 = n_2 = 335$ days.

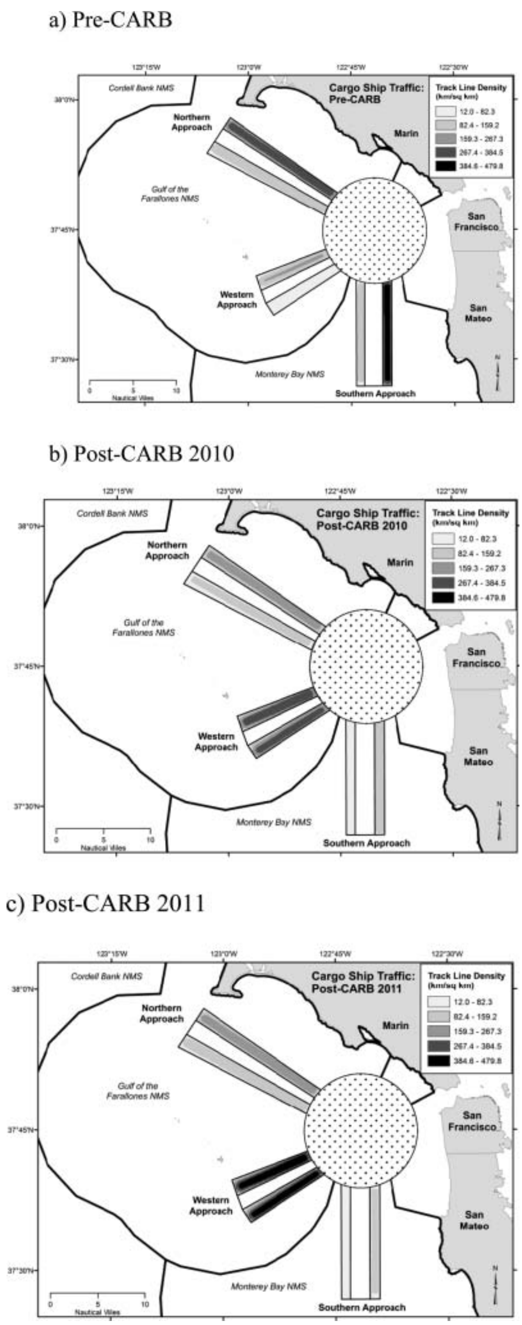

Figure 5. Pre- versus post-CARB shipping density. Track line density maps for (a) Pre-CARB, (b) Post-CARB 2010, and (c) Post-CARB 2011 periods.

Our analyses show that shipping traffic off San Francisco is dynamic at both interannual and daily temporal resolutions, but that traffic was fairly consistent among the seasons considered. At the interannual resolution, our analyses emphasize the importance of economic and regulatory drivers on shipping traffic. Although we were only able to compare Pre- versus Post-CARB traffic for January–May, it is likely that the regulatory influence of the CARB rule on shipping occurred year round because the only seasonal differences observed in the traffic patterns appeared to be driven by changes in the economy. These analyses highlight the need to archive AIS data; without time series of AIS data, changes in shipping traffic cannot be effectively documented.

Shipping traffic is expected to continue to change off the U.S. west coast and to increase in other areas around the world. For example, the Environmental Protection Agency implemented a requirement for all vessels traveling within 200 nmi of the coastline to use fuels containing less than or equal to 0.1% sulfur on January 1, 2015 (Grasso, Waldron, and Merkel 2012). In response, CARB is conducting a review to determine whether or not the fuel rule will be rescinded (CARB 2014). Additionally, decreases in fuel costs could reduce the motivation to use routes that occur farther offshore. In the Southern Hemisphere, macroeconomic, operational, and competitive factors will drive changes in maritime shipping following the expansion of the Panama Canal (Rodrigue 2010a). Patterns of shipping traffic between Asia and Europe are also anticipated to change as sea ice melts in the Arctic (Reeves et al. 2014).

It is important to recognize the dynamic nature of shipping traffic when assessing the risk of ships striking whales. For example, increased traffic in the Northern Outbound lane from San Francisco Bay could be a concern because this lane occurs in an area of predicted humpback (Dransfield et al. 2014) and blue (Irvine et al. 2014) whale habitat. The expansion of the Panama Canal could also alter ship-strike risk for humpback whales because movements of humpback whales wintering in the Gulf of Panama overlap with major commercial shipping routes entering and leaving the Canal (Guzman, Gomez, and Guevara 2012). The increasing use of shipping routes in the Arctic, which overlap with bowhead and beluga whale distributions, could lead to increased ship-strike risk for these species (Reeves et al. 2014). Future research for our study area and other parts of the world should also consider vessel speed when assessing the risk of ships striking whales because the probability that a strike is lethal increases at higher speeds (Conn and Silber 2013; Vanderlaan et al. 2008; Wiley et al. 2011).

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Supplemental Materials

Supplementary material is available for this article at http://dx.doi.org/10.1080/08920753.2015.1086947

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