Exploring Ship Traffic Variability off California

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Declarations

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Abstract

Seaborne trade continues to grow and is an important component of the global economy. Threats from shipping to marine ecosystems include oil spills and other water pollution, air pollution, anchor scouring, biological invasions, container loss, chronic noise, and collisions between ships and large whales. Shipping and its associated threats can be influenced by a suite of regulations and economic events. The dynamic nature of ship traffic can be characterized using ship tracking data from automatic identification system (AIS) technology. These data enhance our ability to analyze the ecological threats from commercial shipping as a component of spatially explicit risk assessments. We explore ship traffic variability using a case study in waters off California. AIS data from 2008-2015 were used to evaluate the role of vessel emission regulations and economic events on vessel routes and speeds. We document vessels navigating around emission control areas (ECAs) or reducing speed when traveling through them. Large freight vessels decreased speeds from 2008 to 2015 by about 3-6 knots in many areas, with lowered speeds observed in areas of both heavy and sparse vessel use. The timing and location of the speed reductions appear to be most influenced by state and international clean fuel standards, which required the use of more costly fuels. Therefore, the speed reductions may have provided a more cost-effective means of travel. We also found temporary speed increases off southern California when vessels used longer routes to avoid traveling through an ECA. We conclude that the establishment of ECAs had a profound influence on vessel routes and speeds, likely due to the higher costs of clean fuels. Proposals have come before the International Maritime Organization (IMO) to establish clean fuel requirements in various locations around the world to reduce air-borne emissions from vessels. Our research suggests such proposals, or other events that may affect marine fuel prices, can have key impacts on vessel behavior. Consequently, it is important to consider this variability when designing strategies to minimize threats from shipping to vulnerable biophysical systems.

Keywords: maritime shipping, automatic identification system, air pollution regulations, cetaceans, slow-steaming, fuel prices

1.0 Introduction

Seaborne trade and the number and size of sea-going, self-propelled merchant ships have increased over the last century with brief breaks related to major economic events, such as the recent global financial crisis and the oil crises of the 1970s (Rodrigue, 2017). Since World War II the number of vessels has generally grown and, in recent decades, average vessel size has increased in part due to advances in containerization (Kemp, 2015; Rodrigue, 2017). Recent estimates indicate that between 80% (UNCTAD, 2016) to 90% (ICS, 2017; IMO, 2012) of world trade is carried over the seas. Tournadre (2014) found a fourfold growth in worldwide traffic between 1992 and 2012 using satellite altimetry to estimate shipping traffic density. The largest increases in traffic were estimated in the Indian Ocean and Chinese seas, but significant increases were detected in most ocean areas (e.g., a two- to three-fold growth in traffic in the northern Pacific).

This increasing reliance on ocean-going vessels can create growing pressures on the ocean and coastal environments. Furthermore, routes frequently occur in ecosystems that are important to marine organisms (e.g., whale feeding areas (Redfern et al., 2013)). Oil spills and other water pollution, air pollution (e.g., related to ocean acidification), anchor scouring, container loss, and biological invasions are examples of threats to marine ecosystems from shipping (Andersson et al., 2016; Davis et al., 2016; Drake, 2007; Hassellöv et al., 2013; Ruiz et al., 2000; Schiel et al., 2016). For cetaceans such as large whales, noise created by vessels can degrade their habitat (Erbe et al., 2012; Hatch et al., 2008; Hatch and Wright, 2007; Redfern et al., 2017) and change their behavior (Holt et al., 2011; Holt et al., 2009), and vessel strikes can directly harm or kill them (Jensen and Silber, 2004; Laist et al., 2001; Redfern et al., 2013; Rockwood et al., 2017). Pressures and threats created by maritime shipping can be influenced by a suite of regulations and economic events. For example, Frisk (2012) showed that a long-term increase in low-frequency ambient ocean noise, in a frequency band important to marine mammals, can be linked to growth in commercial shipping and the global economy. International treaties, such as the International Convention for the Safety of Life at Sea (SOLAS) and the Internation Convention for the Prevention of Pollution from Ships (MARPOL), have provided some direct and ancillary mitigation of some of these risks.

We explore ship traffic variability off California from 2008 to 2015 as a case study. California has two of the largest ports in the world (WSC, 2017): the Ports of Los Angeles (POLA) and Long Beach (POLB) (Fig. 1a). Substantial vessel traffic also occurs in the San Francisco Bay area, which includes the Port of Oakland (a major port for container vessels). Waters off California also contain large military testing/training regions and four national marine sanctuaries that are managed by the National Oceanic and Atmospheric Administration (NOAA) Office of National Marine Sanctuaries (ONMS) (Fig. 1a). Finally, these waters are habitat for approximately 24 cetacean species, including many species of large baleen whales (Becker et al., 2016; Calambokidis et al., 2015; Mate et al., 2015; Weller et al., 2012; Williams et al., 2011): fin whales (*Balaenoptera physalus;* year-round), blue whales (*Balaenoptera musculus;*

summer/autumn feeding), humpback whales (*Megaptera novaeangliae;* summer/autumn feeding), and gray whales (*Eschrichtius robustus;* winter/spring migration between breeding/calving and feeding areas). These whale species are protected (directly or indirectly) by the Marine Mammal Protection Act (MMPA, 1972) and the National Marine Sanctuary Act (NMSA, 1972), and many are protected by the Endangered Species Act (ESA, 1973).

Regulatory changes that impacted the maritime shipping industry have also occurred off California (Table 1). In particular, the California Air Resources Board (CARB) implemented the Ocean-Going Vessel Fuel Rule (OGV Rule) on July 1, 2009. The OGV Rule delineated a California Emission Control Area (CA ECA) from the coast out to 24 nmi. Within the CA ECA, the OGV Rule required vessels to use cleaner burning fuels. The OGV Rule was intended to reduce the impact of vessel emissions on the environment and public health in coastal regions. However, many ships altered their routes to minimize time spent using the more costly cleaner fuels. For example, in the three-week period centered on July 1, 2009, we estimate the weekly average fuel prices for marine diesel oil were higher than typical bunker fuel prices by a range of approximately $168-199/MT or +39.7 to +52.9% (Platts, 2017; TSA, 2017). Jensen et al. (2015) studied shipping traffic off the San Francisco Bay area from January-May in 2009-2011 and found that traffic shifted away from coastal approaches to offshore approaches following implementation of the OGV Rule. McKenna et al. (2012) found a reduction in chronic noise from shipping in the Santa Barbara Channel (SBC) from February 2007 to December 2010 as a result of the Great Recession and the OGV Rule. Redfern et al. (2013) found changes in ship-strike risk for humpback and fin whales in the Southern California Bight (hereafter, the Bight) based on altered traffic patterns from 2008 to 2009. The shift in traffic off southern California may also have resulted in potential conflicts between military training and shipping interests (Redfern et al., 2013). In response to this and other concerns about the effectiveness of the OGV Rule, CARB extended the CA ECA boundary to include the area around the Channel Islands in the Bight (CARB, 2011) (Fig. 1b). The boundary was also officially receded near the ends of the SBC and southern approaches of the traffic separation scheme (TSS) in the Bight to encourage traffic to return to the TSS. This change was implemented on December 1, 2011. The impacts of the OGV Rule on vessel traffic along the entire California coast and after 2011 have not been documented.

Other changes (Table 1) include the implementation of the North American ECA, which increased international standards for clean fuels within the U.S. Exclusive Economic Zone (EEZ), but which did not exceed California clean fuel standards. The United States and Canada (later joined by France for very small territorial waters near Newfoundland) worked with the International Maritime Organization (IMO) to adopt this ECA (hereafter, IMO ECA) which became effective on August 1, 2012. The impact of this IMO ECA on vessel traffic was assessed by Schaumeier et al. (2015) using data collected from 1 January to 31 December 2012. However, this study did not focus exclusively on the U.S. west coast and it excluded data for the CA ECA. Also, during our study period, fuel standards (sulfur limits) became more stringent over time for both the CA ECA and the IMO ECA. In addition, the IMO and the USCG modified the TSSs off California to reduce the risk of vessel collisions with several large whale species.

A number of important economic events also occurred, including the 2007-2009 Great Recession and global economic downturn (Jung et al., 2009), changes in fuel oil markets and prices, and labor disputes at U.S. west coast ports (Phillips, 2015). A number of voluntary and incentivization programs (i.e., offering some financial benefit and a positive public relations campaign) designed to reduce vessel speeds were also implemented in this period. These vessel speed reduction (VSR) programs were initiated in an attempt to reduce ship-strike risk to whales, to reduce vessel emissions, or both.

We used automatic identification system (AIS) vessel data to evaluate variability in ship traffic off California. In particular, we assess how changes in shipping routes and vessel speeds are affected by regulatory changes, economic events, and voluntary initiatives (Table 1). Finally, we explore the potential ecosystem impacts of these changes in shipping traffic.

Event	Date	Type (Geographic Scope)
Start of Great Recession	December 1, 2007	Economic (International)
OPEC agrees to cut oil production	December 17, 2008	Economic (International)
End of Great Recession	June 30, 2009	Economic (International)
California ECA in effect by CARB (1.5%/0.5% Sulfur)	July 1, 2009	Regulatory – Air Quality (California)
Disruption of Libyan oil production (Arab Spring)	March 1, 2011	Economic (International)
California ECA boundary modification by CARB	December 1, 2011	Regulatory – Air Quality (California)
Global fuel standard made more stringent by IMO (3.5% Sulfur)	January 1, 2012	Regulatory – Air Quality (International)
North American ECA in effect by IMO (1.0% Sulfur)	August 1, 2012	Regulatory – Air Quality (North America)
California ECA standard made more stringent by CARB (1.0%/0.5% Sulfur)	August 1, 2012	Regulatory – Air Quality (California)
Traffic separation schemes (TSSs) modified in central and southern California by IMO/USCG	June 1, 2013	Regulatory (USCG)/Advisory (IMO) – Ship Strike (California)
California ECA standard made more stringent by CARB (0.1%/0.1% Sulfur)	January 1, 2014	Regulatory – Air Quality (California)
Start of work slowdown at U.S. west coast ports	October 1, 2014	Economic (California)
North American ECA fuel standard made more stringent by IMO (0.1% Sulfur)	January 1, 2015	Regulatory – Air Quality (North America)
Labor dispute settlement for U.S. west coast ports	February 20, 2015	Economic (California)
Voluntary and Incentivized Programs for Vessel Speed Reduction (VSR):		
Ship Strike VSR (NOAA ONMS)	Start Year: 2012 (full program not in place until 2015) Period: May 1 – November 15 On-going	Voluntary – Ship Strike (Central California: Bay Area TSS)
Ship Strike VSR (NOAA ONMS)	Start Year: 2007 Period: June - November (varies year to year) On-going	Voluntary – Ship Strike (Southern California: Santa Barbara Channel)
Port of Long Beach (POLB) Green Flag Program	Start Year: 2005 20 nm range; extended to 40 nm range from port in 2009 On-going	Incentivized Voluntary – Air Quality (Southern California: near POLB)
Port of Los Angeles (POLA) VSR Program	Start Year: 2008 20 nm range; extended to 40 nm range from port in 2009 On-going	Incentivized Voluntary – Air Quality (Southern California: near POLA)
Protecting Blue Whales and Blue Skies	Start Year: 2014 Period: July 1 – November 15 On-going; expanded to San Francisco Bay Area in 2017	Incentivized Voluntary – Air Quality/Ship Strike (Southern California: Santa Barbara Channel; Central California: Bay Area TSS)

Table 1
A summary of regulatory changes, economic events, and voluntary initiatives affecting waters off California are listed in chronological order. (Note: Sulfur limits are mass by mass (m/m). CARB limits presented for marine gas oil (MGO) first and then marine diesel oil (MDO). Compatible International Organization for Standardization (ISO) fuel grades are DMA/DMZ (MGO) and DMB (MDO).)

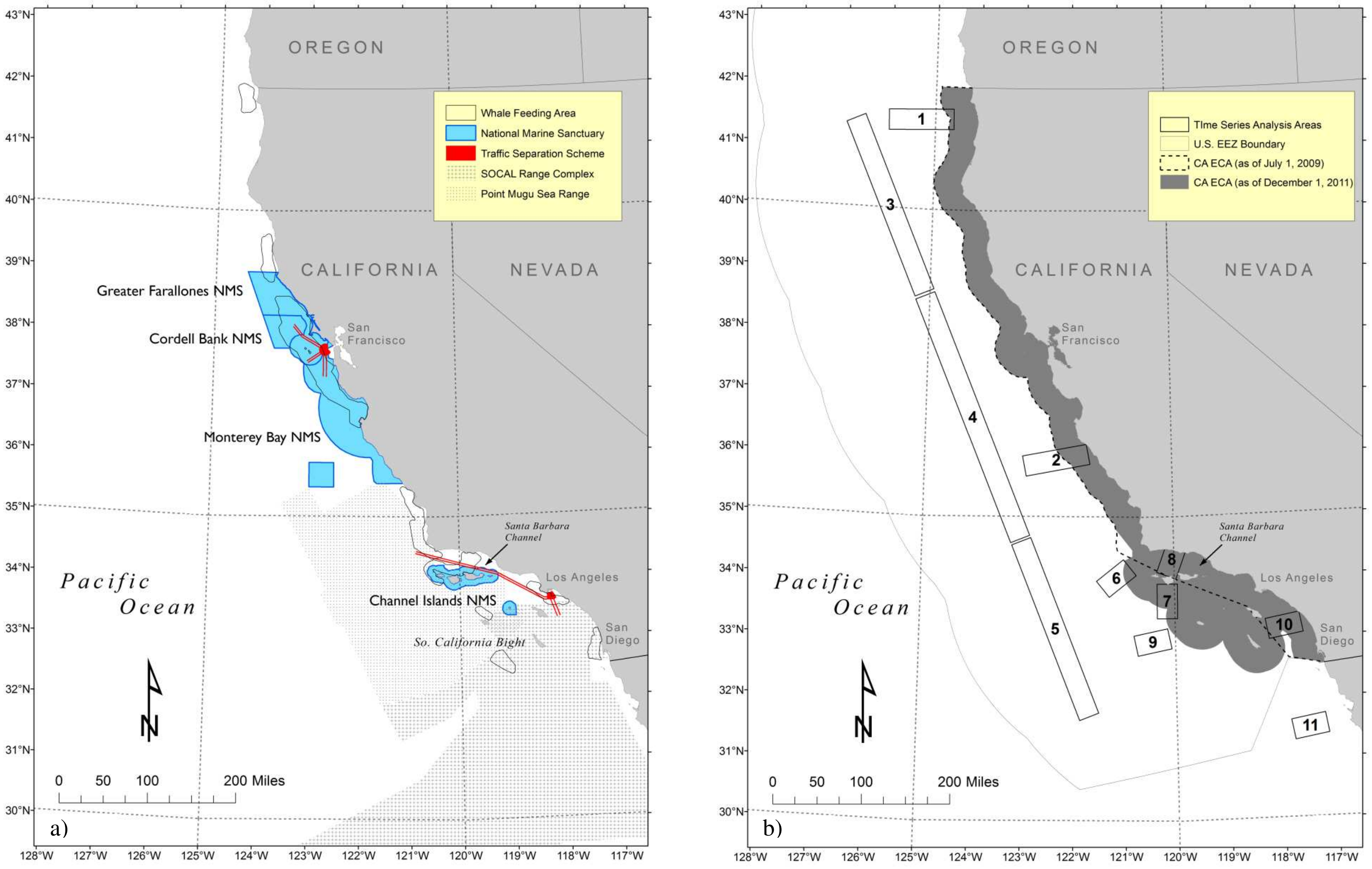

Fig. 1

a) The study area includes two traffic separation schemes (San Francisco Bay Area and Southern California Bight), two military training ranges, four national marine sanctuaries, and documented biologically important areas (Calambokidis et al., 2015)for large whales (e.g., known blue and/or humpback whale feeding areas are shown; gray whales use the coast in a seasonal migration between feeding and breeding/calving areas beyond California). b) The California Emission Control Area (CA ECA) as implemented in July 2009 and modified in December 2011. Also shown is the United States Exclusive Economic Zone (EEZ) boundary which corresponds to the extent of the North American ECA (IMO ECA) boundary in this region, a measure endorsed for implementation in August 2012 by the International Maritime Organization (IMO) and federal partners. The eleven identified locations are used to analyze changes in monthly mean vessel speed and transits/day, and these numbers (as L1 through L11) are used to identify these zones in this analysis.

2.0 Methods and data

AIS is a standard for identifying and tracking vessels. Requirements for carrying AIS were adopted by the IMO as part of the SOLAS treaty in 2000 to improve navigational safety. Carriage requirements continue to evolve internationally and at state levels. In the United States, carriage requirements are administered by the United States Coast Guard (USCG) (USCG, 2017b). Robards et al. (2016) provide an in-depth background on AIS and present a comprehensive review of conservation research and policy applications, including discussions of challenges and recommendations when using these data.

Our AIS data came from the Nationwide AIS (NAIS) terrestrial network deployed by the USCG (USCG, 2017c). We obtained data for June 2008 through December 2015 from the USCG Navigation Center (NAVCEN) at a down-sampling rate of approximately one minute. The USCG began archiving data in June 2008 and do not have data from before this time. AIS message types and data elements are described in USCG (2017a). AIS represents "big data" with a high volume of records on vessel postions at known times, speed over ground (SOG), course over ground (COG) and various fixed data like vessel types, identifiers, and dimensions. The vessel types recorded in AIS data are limited to broad classes, such as passenger, cargo, and tanker. Additionally, vessel identifiers (like vessel name, IMO number, and the maritime mobile service identity (MMSI) of the associated AIS equipment) and characteristics (e.g., vessel length overall, or LOA) can sometimes be missing, incorrect, or incomplete. To overcome these issues, we obtained vessel catalog data from the USCG Authoritative Vessel Identification Service (AVIS) in February 2016 (USCG, 2016). We used the AVIS data to improve our LOA assignment and refine our vessel type classifications to vessels in freight service (e.g., container, general cargo, bulk carrier, refrigerated cargo, vehicle carrier, etc.), vessels in tanker service (e.g., crude oil, chemical/products, liquid petroleum gas, etc.) and vessels in other service (e.g., passenger cruise ships, ferries, etc.).

Our data set is robust over much of the continental side of the EEZ because the USCG network was designed to improve navigational safety, search and rescue, and maritime security. To ensure the best coverage for our analyses, we focus on coastal locations and assess changes through time in either a single location or locations that occur at a similar distance from shore.

All spatial data processing and data analysis were performed with ArcGIS 10.4.1, the Spatial Analyst extension, and the arcpy site package for Python (Esri, 2015). We used Python version 2.7.10 (64-bit) for automation (Python Software Foundation, 2015).

The methods used to build vessel transits from the position reports are presented in detail in the supplemental information. We limited our analysis to vessels greater than or equal to 80 m LOA because Laist et al. (2001) found that larger ships have a greater likelihood of causing severe and lethal injuries to large whales from ship strikes.

Vessel transits were generated in three separate sub-regions (southern California, central California, and northern California) to manage the size of the data processing task. The sub-regions overlap by 30 nm to ensure that a complete representation of ships transiting across an edge will be captured in subsequent raster grid-based analysis (i.e., to eliminate any data loss where transit segments crossing the edge may be omitted due to a missing vessel position report beyond the edge). We chose a distance of 30 nm for the region of overlap based on vessel speeds and the temporal resolution of the AIS data.

We created grids of traffic density (cumulative distance traveled in km) and distance-weighted mean SOG using an Albers equal-area projection for our U.S. west coast study area. Grids were created for a calendar year to assess long-term trends. We used the LineStatistics Tool to generate raster surfaces from the transits in 1 km grid cells. This analysis used a search radius of 564.2 m to ensure the area searched was equivalent in size to the total area of the grid cell (i.e., $\pi r^2 = (1000\ \mathrm{m})^2$). To account for data gaps in some years (e.g., no available data for January to May 2008 and scattered data gaps in 2008 and 2010), we divided the cumulative distance traveled in each grid cell by the number of days of data collection, resulting in traffic density estimates of mean km/day. We used the number of hours in the available data to estimate that there were 112 days of data collection in 2008 and 352 in 2010; all other years had 365 days of data collection (366 in 2012). We analyzed data for all large vessels (combined), as well as large vessels in: a) freight service and b) tanker service. We removed spurious seams where the sub-regions overlap using the MosaicToNewRaster method and selecting the largest cell value. Finally, we calculated the change in traffic density from year-to-year on a grid cell basis so that we can better investigate the nature of annual trends in a spatial context.

We created monthly vessel SOG time series in eleven key zones (see Fig. 1b). These zones were located in areas of large cross-zone traffic flows based on predominant vessel routing in the region. We also located these zones in areas that would allow us to isolate and explore economic and regulatory factors likely to affect vessel traffic patterns (e.g., related to the location of the CA and IMO ECA boundaries). Each zone is defined by a 10 nm buffer around a centerline (i.e., each area has a 20 nm width). Transits within each area were clipped with the Clip Tool and used to calculate the monthly number of transits and distance-weighted mean SOG. The monthly number of transits was estimated by counting the unique vessel transit identifiers in each area. The number of transits was then normalized for each month based on the number of days of AIS data collection (transits/day). These eleven zones represent differently sized geographic areas. Consequently, it is not appropriate to compare transit rates (transits/day) for differently sized zones, but this is not a concern when comparing mean values (for vessel speed).

We used the R (version 3.3.1) statistical package (R Foundation for Statistical Computing, 2016) to conduct an analysis of variance (ANOVA) on monthly vessel SOG to assess significance of vessel speed changes relative to regulatory changes. We focused on monthly mean SOG for the central California offshore zone (L4), the western approach to POLA/POLB (L7), and the SBC (L8) to determine whether vessel speeds were significantly different within different vessel emission regulation periods. These locations were selected because they were exposed to different vessel emission regulations throughout the study period and because they connect ship traffic between the northern Pacific Ocean and the POLA/POLB.

Finally, we also summarized weekly prices for bunker and clean fuels that were likely used during this period (we will use the term "bunker fuel" to identify conventional fuels and to distinguish them from cleaner fuels). We obtained weekly average bunker fuel price data for the U.S. west coast (September 2008-December 2015) from the Transpacific Stabilization Agreement (TSA) website (TSA, 2017). We also calculated the weekly low-sulfur fuel price from the bunker fuel price using the weekly price differential provided by TSA. The low-sulfur fuel price data from TSA begin in June 2012. Consequently, we also obtained marine fuel price data (June 2008-December 2015) for fuel delivery in Los Angeles (ex wharf) for three fuel types (intermediate fuel oil (IFO) 380 centistokes 3.5% sulfur, marine diesel oil (MDO), and marine gas oil (MGO)) to compare to the TSA time series (Platts, 2017). We obtained real gross domestic product (GDP) quarterly data for the United States to represent the overall economic trends during the period. The GDP data were obtained from the U.S. Burea of Economic Analysis (BEA, 2016) in chained dollars (2009) and are seasonally adjusted at annual rates. We selected the sum of imports and exports for the Goods category because of this category's relevance to maritime shipping. The quarterly data were interpolated to monthly values using a cubic spline interpolation in R ("fmm" spline of Forsythe, Malcolm, and Moler (Forsythe et al., 1977)). We also obtained stranding data for large whale species in California from 2008 to 2015 to explore confirmed and suspected ship-strike incidents (NMFS, 2017).

3.0 Results

We present results for large vessels (LOA >= 80 m) in freight service (container, general cargo, etc.) here because they represent a majority of maritime shipping off California. Results for all large vessels (combined) and large vessels in tanker service are included in the supplemental information.

3.1 Annual Vessel Density Patterns

Our analysis shows spatial changes in ship traffic density at both large (e.g., the CA ECA) and small geographic scales (e.g., a TSS) (Figs. 2 and 3). In southern California, west of the POLA/POLB, the traffic occurs primarily in the SBC portion of the TSS in 2008 (Fig. 2a). Some ship traffic shifts from the SBC to a novel western approach south of the northern Channel Islands following the July 2009 establishment of the CA ECA (Figs. 2b and 3a). The number of vessels using this western approach increases in 2010 and 2011 (Figs. 2c-d and 3b-c). In December 2011 the CA ECA boundary is extended farther offshore in this area and ship traffic shifted in 2012 to the outside of the revised boundary (Figs. 2e and 3d) while some traffic appears to return to the SBC (Fig. 3d). Spatial traffic patterns remained similar in 2013 and 2014, but an increasing number of vessels returned to the SBC each year (Figs. 2f-g and 3e-f). In 2015 most ships returned to routes along the TSS in the SBC, although there is still a noticeable flow of traffic on the western approach (Figs. 2h and 3g). Finally, changes in traffic to conform to the TSS modifications on June 1, 2013 (Table 1) for both San Francisco and the SBC can be seen in the 2013-2014 traffic patterns (Fig. 3e-f).

In the eastern part of the Bight, along the southern approach of the TSS, ship traffic off San Diego/Mexico is concentrated in a single flow in 2008 (Fig. 2a). When the CA ECA was implemented in 2009, some of the traffic shifted westward. This pattern remains until the CA ECA boundary was modified in December 2011. After the modification, traffic again becomes concentrated in a single flow and shifts east to align with a concavity in the new boundary (Figs. 2e and 3d).

In central California, ships use three inbound/outbound routes (northern, western, and southern) in the San Francisco Bay TSS. In 2008, density is highest in the northern and southern approaches (Fig. 2a). From the implementation of the CA ECA in 2009, through 2010, traffic shifts away from the northern/southern approaches and concentrates on the western approach (Figs. 2b-c and 3a-b). The number of ships using the western approach continues to increase through 2011, although there is also an increase in traffic on the northern approach (Fig. 3c). In 2012, traffic on the western approach in the inbound lane appears to shift eastward (Fig. 3d), while traffic continued to increase in the northern approach (particularly the outbound lane). From 2013 to 2015, traffic increases on the southern approach (Fig. 3e-g).

Along the central California coast as a whole, between the TSSs in central and southern California, north-south oriented traffic routes shifted westward (offshore) during 2009 and 2010 (Fig. 3a-b). Predominant traffic flows followed this pattern (Fig. 2d-g) until 2015 when the traffic shifts eastward (Figs. 2h and 3g). A similar sequence of shifts appears to have occurred along the coast of northern California (e.g., from north of the Bay Area to the northern border of the state), although the traffic flow is not well-defined due to a more diffuse distribution.

3.2 Annual Mean Vessel Speed

In general, there appears to be a region-wide reduction of vessel SOG (Fig. 4). Between 2008 and 2011, mean speeds are commonly in excess of 20 knots in offshore areas, along the central coast of California, and in some areas approaching ports (Fig. 4a-d). However, by 2014-2015 (Fig. 4g-h) these speeds are generally reduced to 14-18 knots (some exceptions occur along east-west transpacific routes). Speed reductions were observed in the TSSs in the Bay Area and in southern California, and in the western approach to the POLA/POLB. However, temporary speed increases were observed in traffic using the western approach in 2009 (Fig. 4b). In this area, vessel speeds remained relatively high (e.g., as compared to the SBC) through approximately the end of 2011.

3.3 Monthly Time Series of Vessel Speed and Traffic Volume

Monthly mean speeds from June 2008 to December 2015 (Fig. 5a) decrease from 17.8 to 14.3 kts (18.9 max/12.9 min) in central California (L2, Fig. 1b) and from 15.8 to 14.5 kts (16.8 max/13.8 min) in northern California (L1, Fig. 1b). The number of transits (transits/day) trend slightly downward over this period (Fig. 5b). There is a reduction in transits around the time of the ports slowdown and a concomitant speed reduction (particularly in central California; Fig. 5b). Both vessel speeds and number of transits increased as normal operations resumed at the ports. These changes also follow the IMO ECA fuel standard increment on January 1, 2015 in which the sulfur limit is made more stringent and consistent with the CA ECA sulfur limit (see Table 1).

Monthly mean vessel SOG decreased in offshore locations where vessels travel on trans-oceanic trips between ports around the Pacific Rim (Fig. 5c). In particular, speeds decreased from 18.4 to 12.8 kts (19.1 max/12.8 min) between June 2008 to December 2015 in the northern California offshore region (L3, Fig. 1b), from 18.1 to 14.8 kts (19.0 max/14.1 min) in the central California offshore region (L4, Fig. 1b), and from 16.2 to 15.4 kts (18.4 max/14.1 min) in the southern California offshore region (L5, Fig. 1b). The number of transits in the central California offshore region (L4) fluctuates seasonally and is likely linked to economic activity. For the other two locations, the number of transits fluctuates but there is no readily discernible trend over the study period; however, in January 2015, there is an increase in transits in the southern California offshore region (L5, Fig. 1b) and a corresponding decrease in transits in the northern California offshore region (L3, Fig. 1b). This change corresponds to the time when the IMO ECA fuel standard changed (see Table 1), as well as the ports slowdown and subsequent recovery.

Changes in monthly mean SOG and number of transits were observed around the northern Channel Islands in the Bight (Fig. 5e-f) in the area west of San Miguel Island (L6, Fig. 1b; SMI), in the western approach to POLA/POLB (L7, Fig. 1b), and in the SBC (L8, Fig. 1b). In particular, speeds decreased from 15.4 to 13.7 kts (19.3 max/13.6 min) between June 2008 to December 2015 west of SMI, from 17.2 to 13.9 kts (19.6 max/13.6 min) along the western approach, and from 19.4 to 14.5 kts (19.7 max/13.4 min) in the SBC. While all three locations exhibit reductions in mean SOG over the entire period, SOG temporarily increases west of SMI and in the western approach after implementation of the CA ECA. This increase in speed coincides with reductions in the number of transits in the SBC and increases in transits west of SMI and along the western approach. When the CA ECA is expanded to include the area west of SMI and the western approach, speed reductions are observed in those areas and traffic begins to return to the SBC. Monthly SOG values continue to decrease after implementation of the IMO ECA in August 2012 and the subsequent changes in both the CA ECA and IMO ECA fuel standards (the change in the IMO ECA fuel standard also coincides with the ports slowdown). During the spring and summer months of 2015, vessels traveling west of the SMI and along the western approach appear to increase SOG slightly. Traffic also tends to shift from the western approach to the SBC starting in January 2014, which is coincident with the implementation of a more stringent CA ECA fuel standard. Following the implementation of a more stringent IMO ECA fuel standard in January 2015 (to 0.1% sulfur, and consistent with the CA sulfur limit) and the recovery from the ports slowdown, even more traffic shifts from the western approach to the SBC.

In the southern portion of the Bight (Fig. 5g), monthly mean SOG changed from 17.2 to 17.3 kts (18.3 max/14.8 min) between June 2008 to December 2015 in an offshore region (L9, Fig. 1b), from 16.1 to 11.5 kts (16.3 max/11.0 min) in a nearshore region (L10, Fig. 1b), and from 17.8 to 15.4 kts (18.3 max/14.6 min) in a region within the Mexico EEZ (L11, outside the IMO ECA for North America, Fig. 1b). Speeds consistently decreased in the nearshore Bight region. Speeds in offshore Bight region and the Mexico EEZ region also decreased until February 2015, but then increased. This timing generally corresponded to settlement of the port labor dispute and implementation of a more stringent IMO ECA fuel standard. The December 2015 speeds in these regions were some of the highest observed during this time period and the offshore Bight region was the only region to show an increase in speeds at the end of the study period, compared to the start. The number of transits (Fig. 5h) remained fairly constant, although the Mexico EEZ region shows evidence of a seasonal economic cycle (e.g., discernible transit peaks in the summer/autumn periods).

For both the offshore central California location and the SBC, the vessel speeds were significantly reduced in the months following the implementation of the IMO ECA and CA ECA, respectively (Table 2). For the western approach, vessel speeds significantly increased following initial implementation of CA ECA. During this period, ships took longer routes outside of the TSS in the SBC to the POLA/POLB. When the CA ECA was adjusted to include this area of the western approach in December 2011, vessel speeds significantly decreased (also see Fig. 5e-f).

Location	**Emission Control Domain**	**<u>Period 1</u> Pre-CA ECA/ Pre-IMO ECA**	**<u>Period 2</u> CA ECA1*/ IMO ECA*****	**<u>Period 3</u> CA ECA2****	**Significant? (Level)**
Offshore central California (L4)	IMO	17.23 (0.1151)	15.31 (0.0987)	N/A	Yes F=152.96 ($p << 0.001$)
Western approach to POLA/POLB (L7)	CARB	17.61 (0.2250)	18.57 (0.0834)	15.02 (0.0897)	Yes F=336.01 ($p << 0.001$)
Santa Barbara Channel (L8)	CARB	19.10 (0.0958)	15.69 (0.1784)	14.75 (0.0848)	Yes F = 193.47 ($p << 0.001$)

*CA ECA1 is the ECA implemented by CARB for the period from July 1, 2009 – November 30, 2011.
**CA ECA2 is the ECA implemented by CARB as of December 1, 2011 (when the CA ECA boundary was modified).
***IMO ECA is the ECA implemented by the IMO and federal partners as of August 1, 2012.

Table 2
Summary of ANOVA results on monthly mean vessel SOG values at three selected locations (see Fig. 1b) for the period June 2008 – December 2015. Standard errors for the mean are shown in parentheses.

4.0 Discussion

4.1 The Potential Impact of ECAs on Vessel Speed and Traffic Patterns

Our California case study suggests that large freight vessels opportunistically navigated outside ECAs or reduced speed when traveling through them. For example, ships in both central and southern California largely shifted to offshore areas outside the CA ECA when it was implemented in 2009. As the CA ECA was expanded, the IMO ECA was implemented, and more stringent cleaner fuel standards were adopted over time to bring IMO and CA fuel sulfur limits in alignment, traffic began to return to the original nearshore locations. Throughout this entire period (i.e., 2008-2015), SOG decreased in most areas (Fig. 4). The reductions were large (~ 3 to 6 kts) in many of the areas that we analyzed (Fig. 1b and Fig. 5) and were observed in areas of both heavy and sparse traffic (Fig. 4). The exact timing and location of the reductions appear to be influenced by state and federal/international clean fuel standards (e.g., the USCG and U.S. Environmental Protection Agency adopt and enforce the IMO standards in the U.S.), which essentially required the use of more costly fuels (the IMO fuel standard allows the use of exhaust gas cleaning systems, or "scrubbers," to clean vessel emissions if approved by the flag state; in California, clean fuels are currently required, but scrubber technology is under study for compliance by CARB). Areas that had the highest speeds in 2015 or that showed the smallest speed reductions (offshore southern California, offshore Bight, and Mexico EEZ locations) were either outside the IMO ECA (Mexico EEZ) or occur far from California ports in locations that may have a higher percentage of vessels that are not using state ports.

Switching to low-sulfur fuel requires managing fuel viscosity and temperatures, contaminants, and the potential for leaks (Langella et al., 2016). Engine performance issues (including reduced power and failure) may result, but demonstration projects and industry feedback suggest this procedure is routine (EPA, 2010). A study funded by CARB (Jackson, 2011) showed loss of propulsion incidents and other performance issues from fuel switching were very limited around the time of the initial implementation of the OGV Fuel Rule (and the rule has a safety exemption under such circumstances). Fuel switching procedures may last for 0.5 to 1 hours before entering an ECA (Browning et al., 2012), depending on total propulsion power, and vessel speeds may be reduced briefly. If reductions are experienced, the vessel speed changes should be localized along the outside edge of an ECA. Thus, these procedures do not explain the widespread speed reductions observed in our analysis off California (Figs. 4 and 5). The only zone (Fig. 1b) in our time series analysis that may be impacted by these procedures is the zone off SMI (L6) after the CA ECA was extended farther offshore in December 2011. However, the vessel speed reductions in the time series at SMI after December 2011 are smaller than the speed reductions observed in the western approach to POLA/POLB (L7, Fig. 5e), which was well within the CA ECA at that time (Fig. 1b) and in a location where speeds would not be affected by fuel-switching operations.

Adland et al. (2017) found that vessel speeds did not change after the North Sea ECA was implemented. However, these authors acknowledged that compliance monitoring and enforcement activities in Europe might not be as robust as efforts in the North American IMO ECA. Schaumeier et al. (2015) used 2012 AIS data to compare vessel speed in the North American IMO ECA (Canada and the United States), excluding the CA ECA, to speeds in a 200 nm buffer outside of the IMO ECA. Speeds were compared both before and after the IMO ECA implementation on August 1, 2012. Although slightly more vessels traveled slower in the ECA, compared to the buffer area, after the ECA implementation, they did not find that the ECA had a significant effect on speeds. Our results show that speeds were significantly slower in the CA ECA and the IMO ECA off of California, but there are a variety of differences between our analysis and this other study: the geographic and temporal resolutions, the temporal range of the data, the geographic scope, and the methods. Doudnikoff and Lacoste (2014) suggest that vessel speed reductions in ECAs may be offset by speed increases outside ECAs. Off southern California, we observed evidence of increased vessel speeds on the longer route through the novel western approach for the POLA/POLB and outside of the CA ECA, while decreased speeds are identified within the CA ECA (see Fig. 5e-f, Table 2). As the CA ECA subsequently expanded into the western approach to the ports, thus requiring the use of costlier clean fuels, vessel speeds decreased on this longer route and traffic shifted markedly back toward the nearshore route within the SBC. This migration of traffic to the nearshore TSS in the SBC then increased through the end of 2015 as the IMO ECA was implemented and both IMO and CA ECA fuel standards became more consistent. The implementation of a more stringent CA ECA fuel standard in January 2014 accelerated the return of traffic into the SBC (Fig. 5f).

4.2 Slow-Steaming and Marine Fuel Prices

The vessel speed reductions observed off California may be understood more generally in the economic and logistics rationale for the practice of slow steaming given that ECAs are associated with fuel price increments. Slow steaming in maritime shipping has been the subject of on-going discussion in journals, trade publications, and the media, with the underlying motivations explained relative to capacity, demand, and the important role that fuel prices play in the cost-optimization relationship (Barnard, 2010; Dupin, 2015; Kemp, 2015; Leach, 2012; Maloni et al., 2013; Meyer, 2015; Meyer et al., 2012; Notteboom, 2006; Page, 2012; Ronen, 1982, 2011). Rodrigue (2017) notes that the practice seems to have begun around the Great Recession (2008-2009) as demand plummeted and new ship capacity from previously scheduled capital expenditures became available. Ronen (2011) models and tests slow-steaming strategies for container vessel fleets using published data to show a likely approach to optimization: as fuel prices increase (decrease), vessel speeds would trend slower (faster) with more (less) vessels in the fleet deployed into the rotation. Fuel price is particularly important. For example, at a price of 500 USD per ton for bunker fuel, the fuel costs represent three-quarters of the overall operating cost for a large container ship while a price of 135 USD per ton represents one-half of the overall operating cost (Notteboom, 2006). Ronen (2011) and Stanley (2007) also note that concerns over air pollution and the prospect of transitioning to more costly cleaner fuels may further encourage the slow-steaming behavior.

Bunker and clean fuel prices on the U.S. west coast fell precipitously during the last half of 2008 and reached their lowest point in late 2008 through early 2009 (Fig. 6a), a time when the demand and transport of goods also diminished (Fig. 6b). After April 2009, bunker fuel prices rose and stabilized with a subsequent price increase following the Libyan oil disruption associated with the Arab Spring (March 2011). Then, as global clean fuel standards became more stringent by the IMO (January 2012) and the IMO ECA was implemented along with a tightening of CA ECA standards (both in August 2012), bunker fuel prices appear to have been disrupted and gradually fell through 2015. The higher priced clean fuels followed a similar trend throughout, but after the Arab Spring, the price differential relative to bunker fuel increased for the rest of our period of study to roughly \$200-\$400/MT (depending on whether the weekly market or TSA guideline price is used in the comparison). With bunker fuels more likely in demand at the beginning of our study and the demand for cleaner fuels increasing throughout this period, the fuel price curves suggest fuel price may have contributed to the reduction in vessel speeds. Furthermore, the declining clean fuel prices (the clean fuel price in 2015 reached the 2008 bunker fuel price, unadjusted for inflation) may have been related to the vessel speed increases detected during 2015. Recovery from the ports slowdown could also have influenced the 2015 speed increase (Phillips, 2015).

The import/export activity of goods in the U.S. took a significant downturn during the Great Recession and then increased steadily since spring 2009 (Fig. 6b). Contrasting these economic trends with fuel prices (Fig. 6a) in the region (Los Angeles) indicate that major global economic perturbations can play an important role in fuel price markets, as might be expected, but they also demonstrate fuel prices may respond to, among other things, distant geopolitical events (Arab Spring/Libyan oil disruption) and regional factors (ECA clean fuel mandates). However, U.S. regional variations in import/export activity may be present, and the nature of demand facing maritime shipping companies is both globalized and complex.

4.3 Ecosystem Impacts

Our findings indicate that both economic events (changes in fuel prices, recession, and labor actions) and regulations (clean fuel mandates) at regional to global scales influence vessel speeds and routes. This variability can influence the ecosystem impacts of shipping. For example, slower vessel speeds decrease the risk of fatal collisions with large whale species (Conn and Silber, 2013; Vanderlaan and Taggart, 2007), the relative amount of underwater noise introduced by ships (McKenna et al., 2013), and the amount of vessel air-borne emissions (Khan et al., 2012). The reduction in vessel speeds from 19.7 kts to 13.4 kts in the SBC between 2008 and 2015 represents an estimated 20% reduction in the probability that a whale-vessel collision would be fatal (using the relationship between vessel speed and probability of fatality in Conn and Silber (2013) and assuming all other factors remain constant). However, the risk of a strike occurring and the amount of noise could increase if shipping companies increase the number of trips on a route as part of a slow-steaming strategy. Alternatively, the use of increasingly larger ships (due, for example, to the expansion of the Panama Canal (Silber et al., 2015)) may result in a reduction in the overall number of trips (assuming their capacity can be optimized). Repeated, or prolonged, labor actions at some ports can potentially cause shipping companies to use ports in other regions (Kirkham and Khouri, 2015; Phillips, 2015). Therefore, spatially explicit risk assessments are necessary to more fully characterize the ecosystem impacts of shipping variability.

The location of vessel traffic (e.g., offshore versus nearshore and its dynamic nature) may also have important consequences for the risk of ships striking whales and our detection of such events. Our study shows traffic began shifting offshore in mid-2009 in evolving novel routes and returned nearshore to more established routing toward the end of our study period. The average number of detected strandings per year that were confirmed or suspected to be caused by a ship strike decreases from 7.75 (2008-2011) to 2.75 (2012-2015) around our study period (Fig. 7) (NMFS, 2017). The reduced risk of a fatal strike (from reduced vessel speeds) may also have contributed to this reduction in detected ship strikes. These stranding data only represent detected events and do not represent the actual number of whales that were struck by ships off California. The location of ship traffic also has important implications for the consequences of oils spills and air pollution on coastal ecosystems and communities.

VSR programs are an option for continuing to reduce vessels speeds and ecosystem impacts. In California, voluntary VSR initiatives to date show poor compliance with efforts to reduce vessel speeds below 10 knots using blanket seasonal whale advisories, while incentivized approaches show an increase in participation (Freedman et al., 2017). Furthermore, compliance "report cards" have proven effective as a strategy to increase participation and change behaviors with up to a 10% increase in compliance overall from 2015 to 2016, and up to a 40% increase in compliance from individual shipping companies (Carver, 2017). Such initiatives offer reductions in ship strike risk (and air pollution), but to date have not achieved a high level of compliance across the industry. Our study shows the capacity of the industry to reduce vessel speeds significantly over time, but further speed reductions can offer substantial reductions in ship-strike risk and air pollution. The incentivized VSR programs of the POLA/POLB to reduce vessel emissions in proximity to these ports have proven to achieve good compliance rates (e.g., Linder (2010) showed compliance rates, as of 2007 for the 20 nm range, of 86% for POLA and 90% for POLB -- well before the period for our study).

The linkages among shipping variability, economic events, and regulations demonstrated in our case study are relevant globally. For example, feeding grounds for a population of blue whales off Sri Lanka overlap with one of the busiest shipping routes in the world (De Vos et al., 2016; Kaluza et al., 2010; Priyadarshana et al., 2016; Tournadre, 2014). ECA strategies have been considered to protect coastal communities in Japan, Australia, Singapore, China, and the Mediterranean Sea. The potential impacts of these proposed, distant ECA implementations on the vessel speeds of ships transiting the Indian Ocean near Sri Lanka are not known. The impact of reduced transit times through the Suez Canal on vessel speeds and ship traffic volumes in the northern Indian Ocean, which might occur as a result of the recent canal expansion project (Saleh, 2015), is also unknown. Finally, there may be effects of changing global marine fuel sulfur limits from 3.5% to 0.5% outside existing IMO ECAs on 1 January 2020 (IMO, 2016). Our research suggests this shipping variability may have important impacts on the Northern Indian Ocean ecosystem. McKenna et al. (2015) suggest that blue whales, and possibly other large whales, may have limited ability to avoid collisions with ships and they may be particularly vulnerable to such risks under varying vessel speeds. Young et al. (2006) suggest that social systems, rather than biophysical systems, may be more resilient to the growing influence of globalization because the central attributes of foresight and reflexivity are inherent in social systems and represent an advantage as the connectivity, speed, and scale of interactions increases (e.g., information, trade, etc.). Therefore, improved consideration and understanding of the dynamic and integrated nature of social systems may provide important insights to adaptively manage and mitigate risks to vulnerable biophysical systems in an increasingly globalized world.

5.0 Conclusions

We analyzed AIS data to assess changes in vessel speed and traffic patterns off California over an eight-year period (2008-2015). This period contained a number of regulatory changes, economic events, and voluntary initiatives that had the potential to influence maritime shipping. Our analysis found significant vessel speed reductions generally across the region, particularly for large freight vessels, during this period. We also document decreased speeds in areas as a likely response to evolving ECA clean fuel requirements, and increased speeds in a region beyond an ECA where the use of costlier clean fuels was not mandated at the time. We also document spatial shifts in traffic offshore in response to ECAs. By the end of our study period, a significant portion of the ship traffic returned to previously used nearshore routes as increasingly stringent clean fuel standards were extended farther offshore. These changes are linked to the potential ecosystem impacts of shipping and show the importance of including shipping variability in spatially explicit risk assessments.

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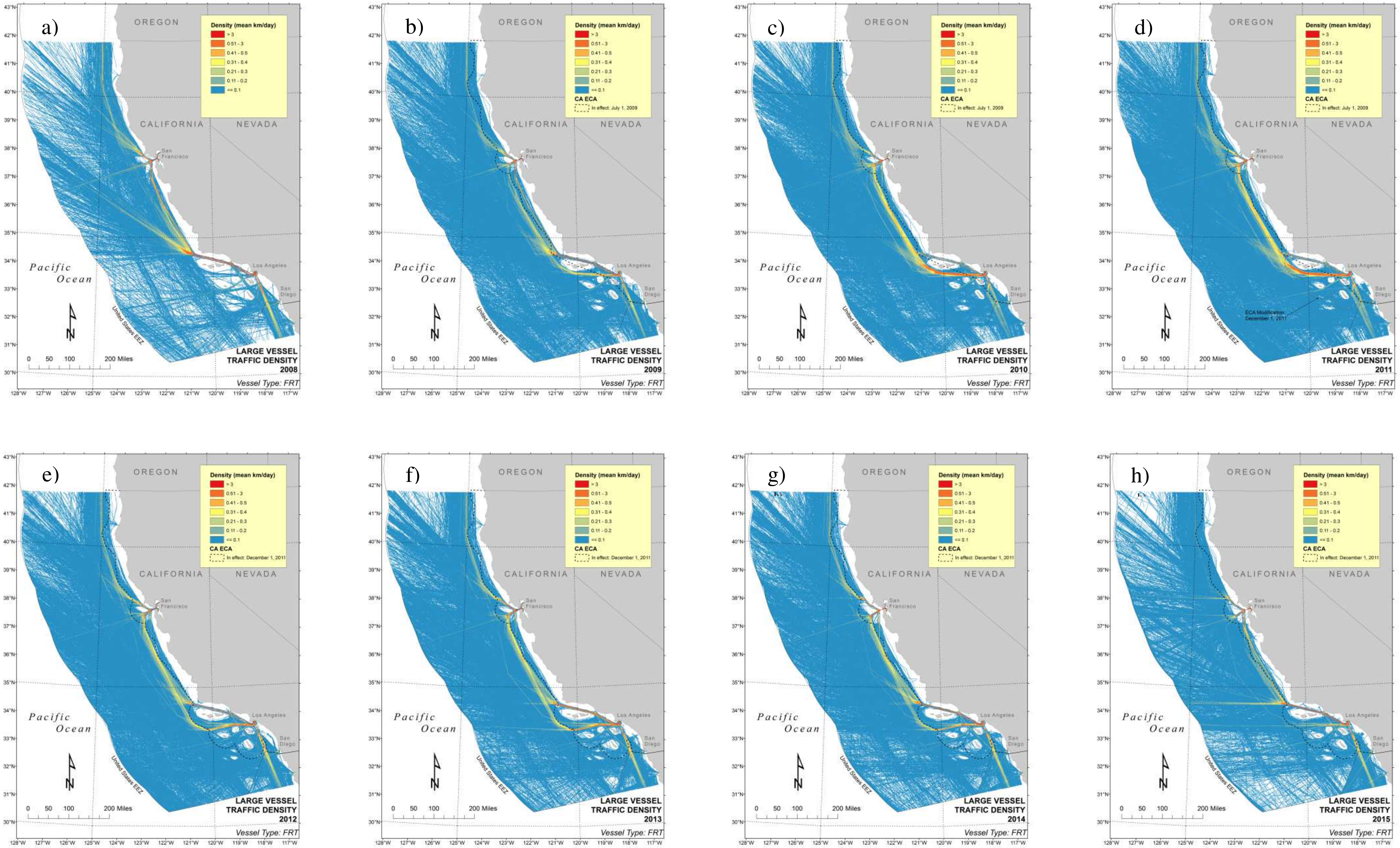


Fig. 2(a-h)
Vessel traffic density (mean km/day) for large vessels (LOA >= 80 m) in freight service during annual periods from 2008 to 2015. The analysis uses a 1-km grid resolution.

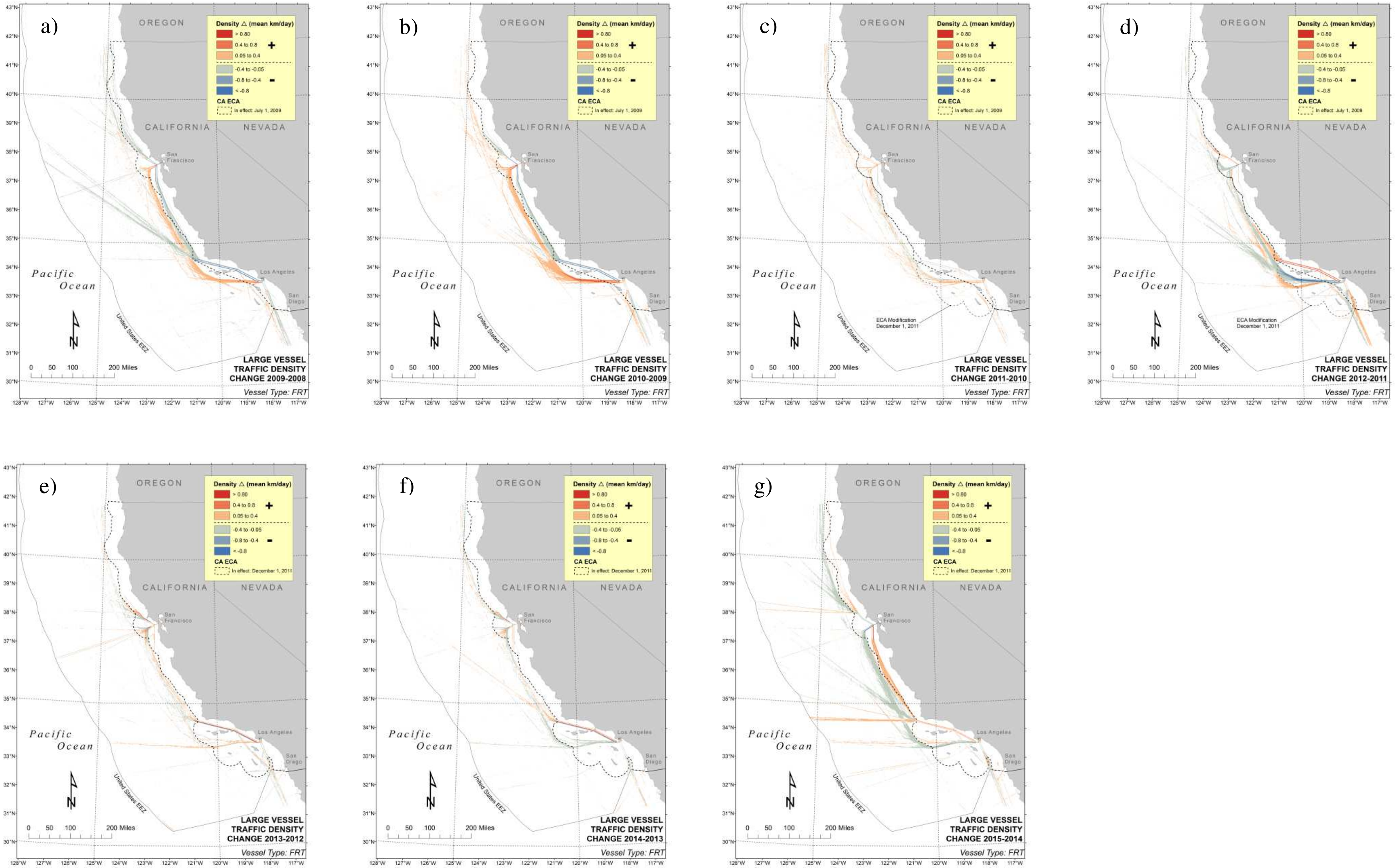


Fig. 3(a-g)

Vessel traffic density change (△ mean km/day) for large vessels (LOA >= 80 m) in freight service during annual periods from 2008 to 2015. The analysis uses a 1-km grid resolution.

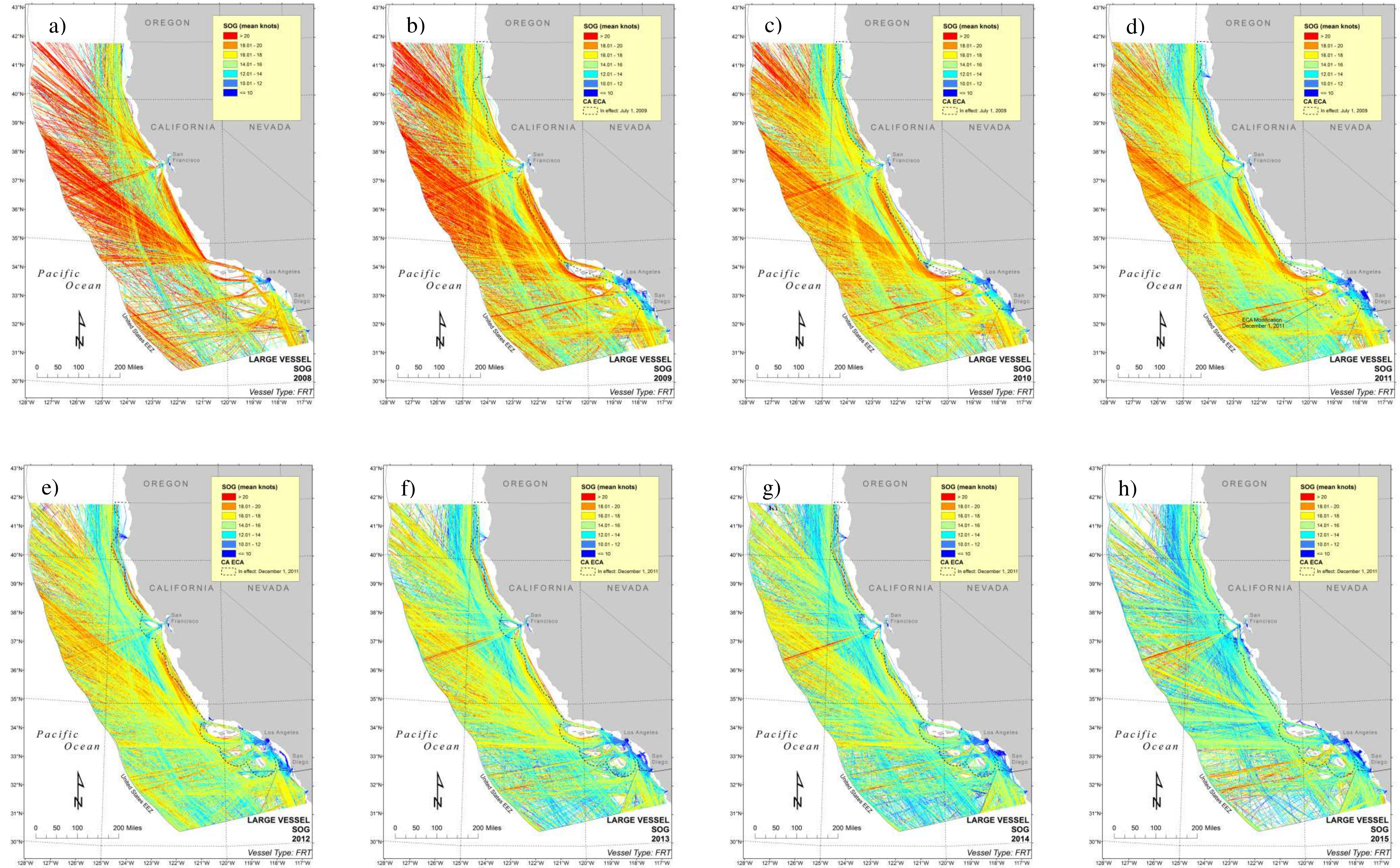
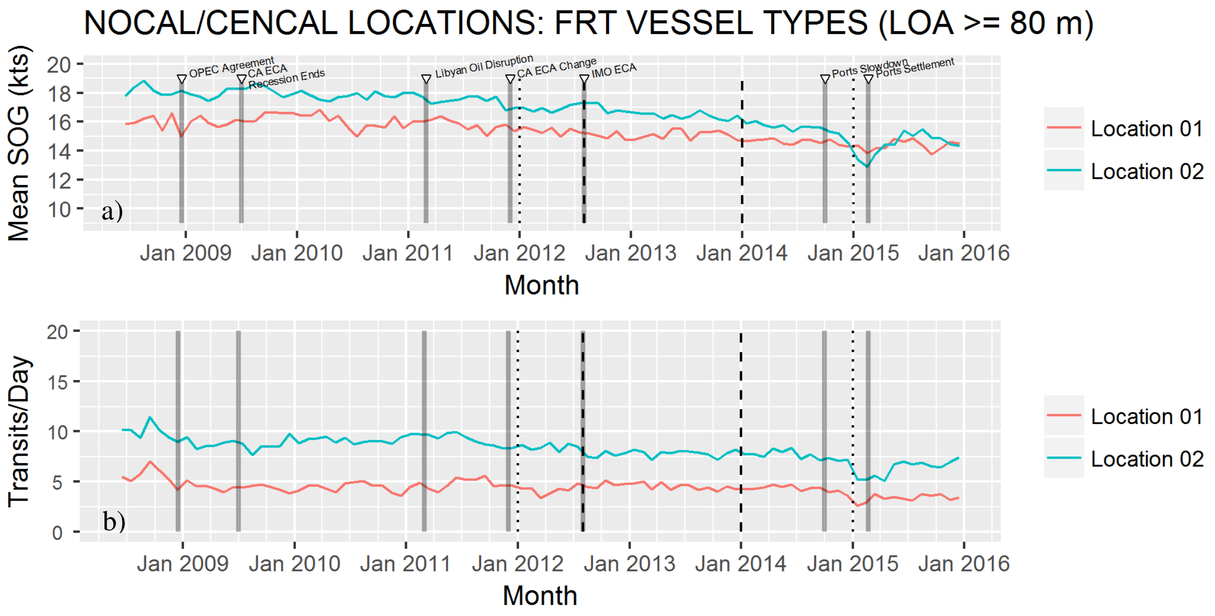
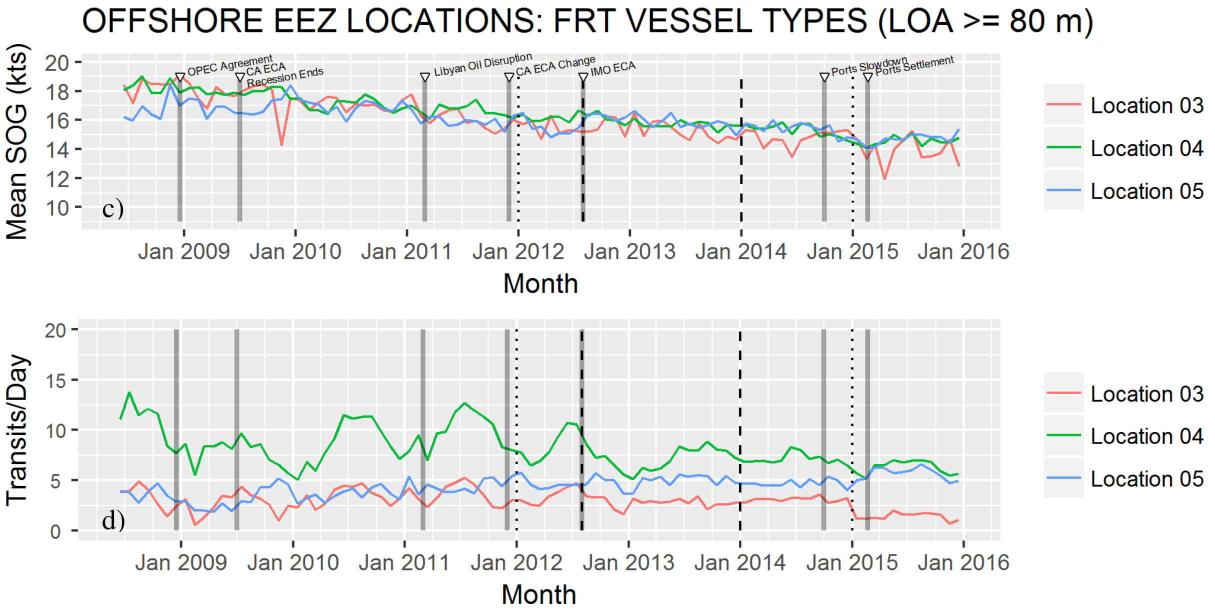


Fig. 4(a-h)
Vessel speed-over-ground (SOG) (mean knots) for large vessels (LOA >= 80 m) in freight service during annual periods from 2008 to 2015. The analysis uses a 1-km grid resolution. Distance-weighted mean values are calculated using transit lengths in proximity to a grid cell.


NOCAL/CENCAL LOCATIONS: FRT VESSEL TYPES (LOA >= 80 m)
Mean SOG (kts)
20
18
16
14
12
10
a)
OPEC Agreement
CA ECA
Recession Ends
Libyan Oil Disruption
CA ECA Change
IMO ECA
Ports Slowdown
Ports Settlement
Jan 2009
Jan 2010
Jan 2011
Jan 2012
Jan 2013
Jan 2014
Jan 2015
Jan 2016
Month
Location 01
Location 02
Transits/Day
20
15
10
5
0
b)
Month
Location 01
Location 02


OFFSHORE EEZ LOCATIONS: FRT VESSEL TYPES (LOA >= 80 m)
Mean SOG (kts)
20
18
16
14
12
10
c)
OPEC Agreement
CA ECA
Recession Ends
Libyan Oil Disruption
CA ECA Change
IMO ECA
Ports Slowdown
Ports Settlement
Jan 2009
Jan 2010
Jan 2011
Jan 2012
Jan 2013
Jan 2014
Jan 2015
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Location 05
Transits/Day
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Location 03
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Location 05

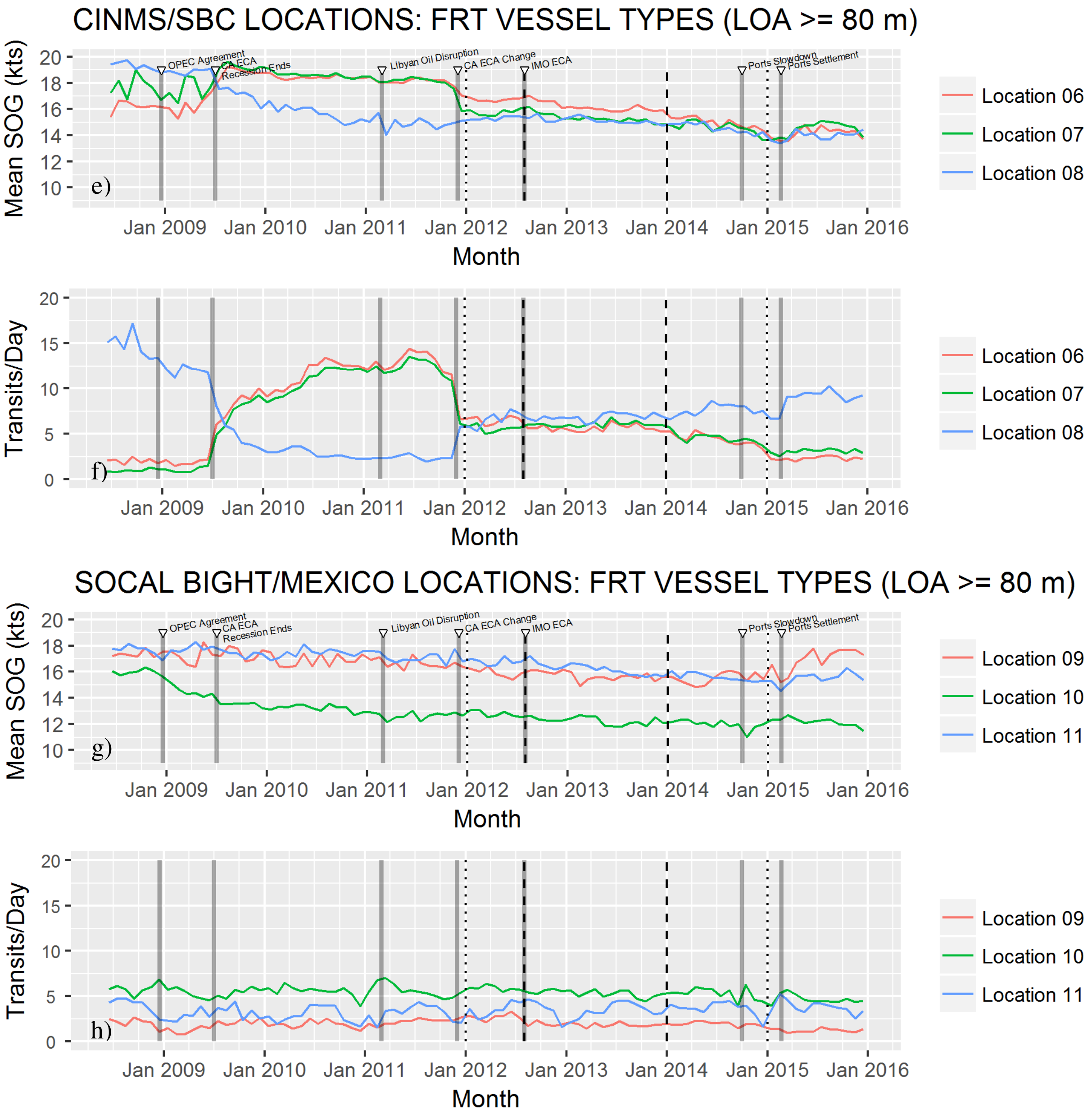

Fig. 5(a-h)

Monthly mean SOG and monthly transits/day within eleven locations in the study region (see Fig. 1b) from June 2008 to December 2015 for large vessels (LOA >= 80 m) in freight service. Key milestones in the timeline are marked with a vertical bar and annotated (see Table 1). CA ECA fuel standards become more stringent at times with black dashed lines while IMO or IMO ECA fuel standards become more stringent at times with black dotted lines (also see Table 1).

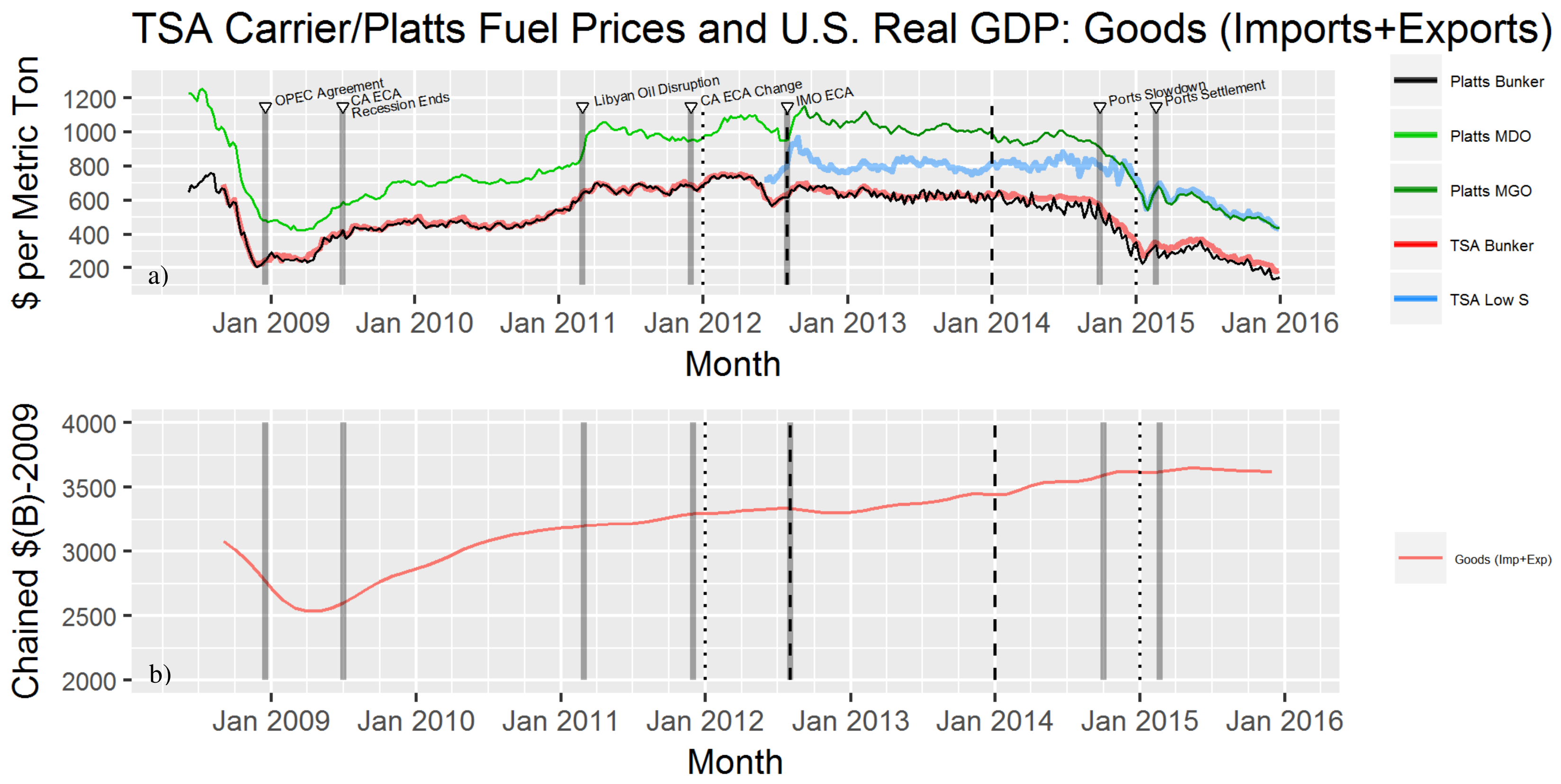

Fig. 6(a-b)
a) Fuel prices (weekly average) for bunker and low sulfur fuels in effect for the U.S. west coast via the TransPacific Stabilization Agreement (TSA) from September 2008 – December 2015 (TSA, 2017). The low sulfur fuel price data record starts in June 2012. Key milestones in the timeline are marked with a vertical bar as in Fig. 5 (see caption). Weekly average fuel prices (ex wharf Los Angeles) are also shown for intermediate fuel oil (IFO 380 CST 3.5%; bunker fuel), marine diesel oil (MDO), and marine gas oil (MGO) from June 2008 – December 2015 (Platts, 2017). b) The component of the U.S. Real Gross Domestic Product (GDP) that is the summation of imported and exported goods.

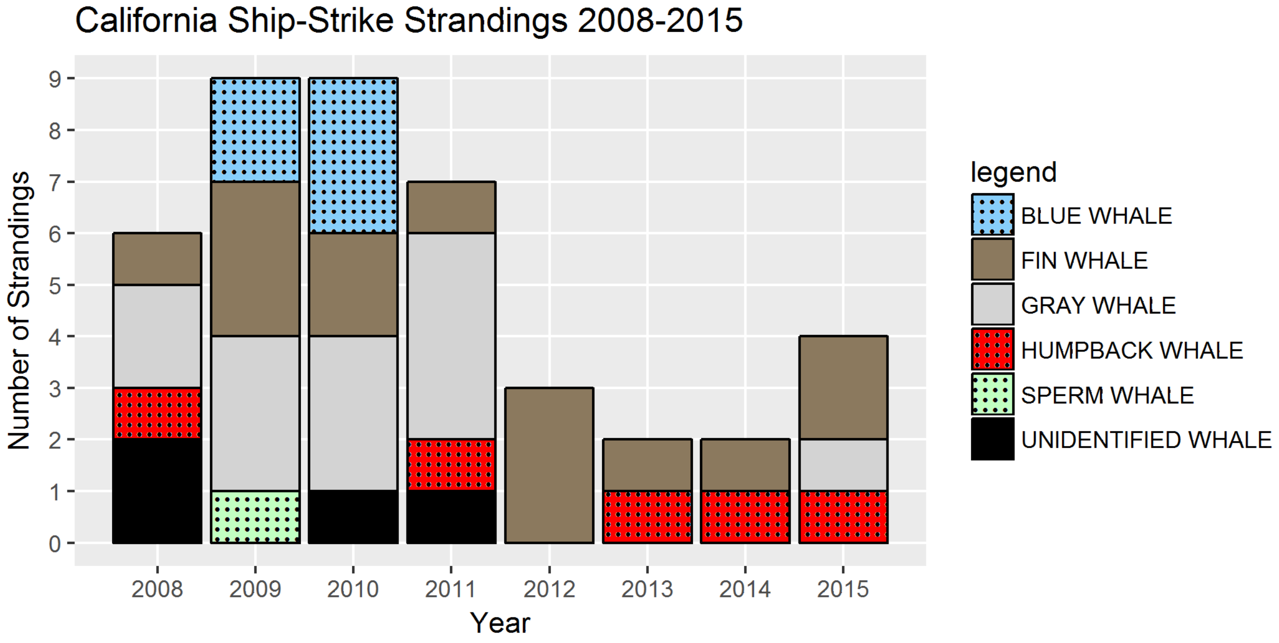

Fig. 7
Annual record of observed whale strandings which are confirmed/suspected to be related to a ship strike in California for 2008-2015 (NMFS, 2017). The stranding counts are categorized by whale species (common name). Of the 42 incidents, 71% had a final status of mortality.